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NEURODESIGN

Modeling With Neural Potentials

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0.1 ABSTRACT (EN)

It seems clear now that the main aspect of how one deal with the grasping of the whole world, including oneself, is of a probabilistic kind. And this is highly linked to the fact that the concept of information has gradually dominated our production of ideas since the 19th c. One must now deal with an overdue time of acceptance that embracing informational and communication models should be most pervasive and necessarily overcome to build a new ground of capacity, another boundary to explore. Such a statement is not to be confused with primitive positivist views but rather intends to express a belief in the models we elaborate to observe and understand ourselves as intelligent humans and, concurrently, how to model the world that surrounds us. The informational paradigm, its inferential and probabilistic approach to information, is taken from many fields involved in perception, cognition and representation of information at many levels and which I believe should provide more contemporary approaches to thinking of architectural modeling, the encoding of parts and their articulations.

Throughout the title (*Neurodesign, Modeling with Neural Potentials*), the term *neural potentials* means twofold: *potentials* as in electric potentials, vessels of information to be decoded, and *potentials* as in *capacity* held by such information. The thesis comprises three main chapters, its conclusion and an appendix containing publications and research materials produced along the research. Its general intent reflected throughout the chapters is to balance the research between empirical and theoretical findings to mutually inform each other on the prototyping of potentially novel ways to approach architectural modeling and its encoding.

The first chapter serves as an expanded *Introduction* into ground contexts and positions for this research. In order to emphasise peculiar circumstances which are laying a base for the main arguments of this thesis, the sections are organised along key notions which have been deprived of some of their constituents, in apophatic terms, and by looking mainly at the past two centuries. The chapter begins with a general introduction to the identified background contexts, the thesis structure, its methods and the theoretical positions which led to these directions. Followingly, the main section develops the *ground contexts* of *modeling intelligence on apophatic grounds* by emphasising on - the obsolescence of particular centralities of scientific thinking after a 20th c. crisis of intuition, and the opportunities revealed for the pursued thinking of computation in architecture (*Knowledge without Center*), - the transformation of reason into rationality and its reapparition in an objective formulation along the same period (*Intelligence without Reason*), - the capacity of models of computation in their incompleteness and complementarity as a potentially more capacious form of modeling with intelligence (*Computation without Universality*), - the computational models dealing with representational theories of the mind and the way some of its elements suggest ways to deal with human cognitive capacity to create non-exhaustive values from the world (*Minds without Meaning*), - the endless search for correlating spatially temporal and dynamic events of the mind which led to abundant ideas about the mechanisation of natural symbolic processing (*Events without Places*), - the overlooked aspect of temporal agency in architectural modeling in regards to the human mind and the way it relates to events and its valuation (*Articulation without Representations*).

These sections are then followed by a synthetic account of the corollary and authored precedents of this research for positing a retroactive reflection before summing the contextual introduction and leading to the main current research question on architectural modeling with neural potentials.

The second chapter (*Modeling with Neural Potentials*) brings the question forward by intending to develop a prototypical theory on architectural modeling with neural potentials. It does so by looking selectively into a broad spectrum of joined ideas in logics, mathematics, computer science, cognitive science, philosophy, art and architecture about intelligence and modeling. Some central concepts and positions are derived from looking into potentially novel architectural modelling approaches. - The first section (*On Models and Modeling*) starts this chapter with a more abstract and general aspect of scientific modeling. It identifies two complementary types of models to support progressive thinking. - The second section (*On Cognition and Memory*) looks into the virtual capacity for human cognition to produce meaning. - The third section (*On Tokens and Beliefs*) derives key ideas of dynamics about informational values from theories of communication and information and through the understanding of vision as a modeling technology. Several permutations are applied for generative architectural modeling and support a more acute way to perform in informational terms. - The fourth and last section (*Architectural Modeling with Neural Potentials*) finally aggregates these developments into an architectural framework focusing on architectonics and modeling with the intent to contribute to the ideas of computation, the generative, and articulations in a progressive way. Accordingly, this chapter concludes with a synthetic summary of its central theoretical contribution.

The third chapter (*Experiments in Modeling with Neural Potentials*) gathers more practical endeavours. It investigates the previously developed ideas into practical experiments encompassing a complementary model of intelligence at the interface between computers and computational accounts of human cognitive vision (in more technical terms, visual *Brain-Computer Interfaces*, or BCI). It is divided into two main sections. - The first section (*Corollary References*) serves as an initial review of the state-of-the-art research in this multidisciplinary field. While progressively identifying key ideas and methods beyond clinical and assistive applications for the subsequent development of experiments, it categorises main components from data acquisition to signal processing and decoding towards the scheme of a general research framework. The second section (*Conducted Experiments*) applies these findings progressively and tries to derive existing BCI models of natural communication of spelling words towards aggregating parts in the visual mode. It begins with the generalisation of a reference model known as the *P300-BCI Word Speller* and points to the generalisation of visual discrimination and its methods for visual modeling. It continues with an adapted version of the spelling model into the generation of shapes and investigates the encoded meaningfulness and its potential dynamics. A third and last experiment augments the reflection. It develops a last computational model which enables both the human capacity for visual discrimination in complex environments and the computer capacity for generating large amounts of probable solutions in a vast solution space. The experiment takes the shape of iteratively aggregating non-trivial parts and posits that such a model enables non-syntactical accounts of generative architectural modeling.

Similarly to previous chapters, it concludes with a summary of found methods in encoding design methods and their segmented domains for a potentially richer exploration of generative solutions in future architectural modeling.

The conclusion draws a synthetic outlook of the thesis and its developed arguments. It starts by abstracting a contribution to the idea of *intelligent* architectural modeling by the way the very modeling of intelligence may show a path to continue with the benefits of computation in architecture and suggests other generative approaches than syntactical *a priori*, in the realm of information and communication. In the positive perspective of pursuing this research, some limitations and near-future developments are mentioned to redefine certain grounds and perspective applications as a new point of departure.

0.2 ZUSAMENFASSUNG (DE)

Es scheint jetzt klar zu sein, dass der Hauptaspekt, wie man mit dem Verständnis der ganzen Welt, einschließlich seiner selbst, umgeht, probabilistischer Art ist. Und dies hängt in hohem Maße mit der Tatsache zusammen, dass die Idee der Information unsere Ideenproduktion seit dem 19. Jahrhundert immer mehr beherrscht hat. Man muss sich nun mit einer überfälligen Zeit der Akzeptanz auseinandersetzen, in der Informations- und Kommunikationsmodelle meist allgegenwärtig sein und notwendigerweise überwunden werden sollten, um eine neue Grundlage der Kapazität, eine andere Art von Grenzen, die es zu erforschen gilt, zu schaffen. Eine solche Aussage ist nicht mit primitiven positivistischen Ansichten zu verwechseln, sondern soll vielmehr den Glauben an die Modelle zum Ausdruck bringen, die wir erarbeiten, um uns selbst als intelligente Menschen zu beobachten und zu verstehen, und gleichzeitig, wie wir die Welt, die uns umgibt, modellieren sollen. Das Informationsparadigma, seine inferentielle und probabilistische Herangehensweise an Information, stammt aus vielen Bereichen, die auf vielen Ebenen mit der Wahrnehmung, der Kognition und der Repräsentation von Information zu tun haben und die meiner Meinung nach zeitgemäßere Ansätze für das Denken in der Architekturmodellierung, der Kodierung von Teilen und ihren Artikulationen liefern sollten.

Im gesamten Werk (*Neurodesign, modeling with Neural Potentials*) bedeutet der Begriff neuronale *Potentiale* zweierlei: Potentiale wie elektrische Potentiale, Gefäße von zu dekodierenden Informationen, und Potentiale wie die Kapazität, die in solchen Informationen steckt. Die Dissertation besteht aus drei Hauptkapiteln, einem Fazit und einem Anhang mit Publikationen und Forschungsmaterialien, die im Rahmen der Forschung entstanden sind. Die generelle Absicht, die sich in den Kapiteln widerspiegelt, besteht darin, über den Zeitraum der Forschung ein Gleichgewicht zwischen empirischen und theoretischen Erkenntnissen herzustellen, um sich gegenseitig über die Entwicklung von Prototypen potenziell neuartiger Ansätze für die Architekturmodellierung und deren Kodierung zu informieren.

Das erste Kapitel dient als eine erweiterte *Einführung* in grundlegende Kontexte und Positionen dieser Forschung. Um die besonderen Umstände hervorzuheben, die die Grundlage für die Hauptargumente dieser These bilden, sind die Abschnitte anhand von Schlüsselbegriffen organisiert, denen in apophatischer Hinsicht einige ihrer Bestandteile entzogen wurden, indem hauptsächlich die vergangenen zwei Jahrhunderte betrachtet werden. Das Kapitel beginnt mit einer allgemeinen Einführung in die identifizierten Hintergrundkontexte sowie in die Struktur der These, ihren Methoden und den theoretischen Positionen, die zu diesen Ansätzen geführt haben. Anschließend entwickelt der Hauptteil die Grundkontexte der Modellierung von Intelligenz auf apophatischer Grundlage, indem er Folgendes in den Fokus nimmt: -Die Hinfälligkeit bestimmter Zentralitäten des wissenschaftlichen Denkens nach der Krise der Intuition im 20. Jahrhundert und die Möglichkeiten, die sich für das weiterführende Denken des Rechnens in der Architektur ergeben haben (*Knowledge Without Center*), - die Umwandlung der Vernunft in die Rationalität und ihre Wiederkehr in einer objektiven Formulierung im gleichen Zeitraum (*Intelligence Without Reason*), - die Fähigkeit von Rechenmodellen in ihrer Unvollständigkeit und Komplementarität als eine potenziell umfassendere Form der Modellierung mit Intelligenz (*Computation without Universality*), - die Computermodelle, die sich mit Darstellungstheorien des Geistes befassen, und die Art und Weise, wie einige ihrer Elemente Wege zum Umgang mit der menschlichen kognitiven Fähigkeit aufzeigen, um nicht erschöpfende Werte aus der Welt zu schaffen (*Minds without Meaning*), - die endlose Suche nach der Korrelation räumlich-zeitlicher und dynamischer Ereignisse im Geist, die zu einer Fülle von Ideen über die Mechanisierung der natürlichen symbolischen Verarbeitung führte (*Events without Places*), - der vernachlässigte

Aspekt des zeitlichen Handelns in der Architekturmodellierung in Bezug auf den menschlichen Geist und die Art und Weise, wie er sich auf Ereignisse und deren Bewertung bezieht (*Articulation without Representations*).

Diesen Abschnitten folgt dann eine synthetische Darstellung der Folgerungen und verfassten Präzedenzfälle dieser Forschung, um eine rückwirkende Reflexion anzustellen, bevor die kontextuelle Einführung zusammengefasst wird und zur wichtigsten aktuellen Forschungsfrage der Architekturmodellierung mit neuronalen Potentialen führt.

Das zweite Kapitel (*Modeling with Neural Potentials*) bringt die Frage voran, indem es beabsichtigt, eine prototypische Theorie der Architekturmodellierung mit neuronalen Potentialen zu entwickeln. Dies geschieht durch die selektive Untersuchung eines breiten Spektrums miteinander verbundener Ideen in Logik, Mathematik, Informatik, Kognitionswissenschaft, Philosophie, Kunst und Architektur über Intelligenz und Modellierung. Anschließend werden einige Hauptkonzepte und Positionen abgeleitet, um potenziell neue Wege für die Annäherung an die Architekturmodellierung zu untersuchen. - Der erste Abschnitt (*On Models and Modeling*) beginnt dieses Kapitel mit einem abstrakteren und allgemeineren Aspekt der wissenschaftlichen Modellierung und identifiziert zwei komplementäre Arten von Modellen zur Unterstützung eines progressiven Denkens. - Der zweite Abschnitt (*On Cognition and Memory*) befasst sich mit der virtuellen Fähigkeit der menschlichen Kognition, Sinn zu produzieren. - Der dritte Abschnitt (*On Tokens and Beliefs*) werden Schlüsselideen der Dynamik über Informationswerte aus Theorien der Kommunikation und Information und durch das Verständnis des Sehens als Modellierungstechnologie abgeleitet. Es werden verschiedene Permutationen für die generative Architekturmodellierung angewandt, die eine präzisere Art und Weise der Informationsverarbeitung unterstützen. - Der vierte und letzte Abschnitt (*Architectural modeling with Neural Potentials*) fasst diese Entwicklungen in einem architektonischen Rahmen zusammen, der sich auf die Architektonik und die Modellierung konzentriert, mit der Absicht, auf progressive Weise einen Beitrag über die Ideen der Berechnung, des Generativen und der Artikulationen zu leisten. Dementsprechend schließt dieses Kapitel mit einer synthetischen Zusammenfassung seines wichtigsten theoretischen Beitrags.

Das dritte Kapitel (*Experiments in modeling with Neural Potentials*) sammelt eher praktische Bestrebungen und untersucht die zuvor entwickelten Ideen zu praktischen Experimenten, die ein komplementäres Modell der Intelligenz an der Schnittstelle zwischen Computern und rechnergestützten Darstellungen des menschlichen kognitiven Sehens umfassen (in technischeren Begriffen: visuelle Gehirn-Computer-Schnittstellen oder BCI). Es ist in zwei Hauptabschnitte unterteilt. - Der erste Abschnitt (*Corollary References*) dient als ein erster Überblick über den neuesten Stand der Forschung in diesem multidisziplinären Bereich, wobei nach und nach Schlüsselideen und -methoden identifiziert werden, die über klinische und unterstützende Anwendungen für die nachfolgende Entwicklung von Experimenten hinausgehen. - Der zweite Abschnitt (*Conducted Experiments*) wendet diese Erkenntnisse progressiv an und versucht, bestehende BCI-Modelle der natürlichen Kommunikation durch Wortbildung abzuleiten, um Teile im visuellen Modus zu verbinden. Er beginnt mit der Verallgemeinerung eines Referenzmodells, das als P300-BCI *Word Speller* bekannt ist, und weist auf die Verallgemeinerung der visuellen Diskriminierung und ihrer Methoden zur visuellen Modellierung hin. Es setzt sich mit einer angepassten Version des Wortbildungsmodells in der Formgenerierung fort und untersucht die kodierte Aussagekraft und ihre potenzielle Dynamik. - Ein drittes und letztes Experiment ergänzt die Reflexion und entwickelt ein letztes Rechenmodell, das sowohl die menschliche Fähigkeit zur visuellen Unterscheidung komplexer Umgebungen als auch die

Computerkapazität zur Erzeugung großer Mengen wahrscheinlicher Lösungen in einem riesigen Lösungsraum ermöglicht. Das Experiment nimmt die Form einer iterativen Aggregation von nicht trivialen Teilen und Stellungen an, die ein solches Modell für nicht syntaktische Darstellungen der generativen Architekturmodellierung ermöglicht.

Ähnlich wie in den vorhergehenden Kapiteln schließt es mit einer Zusammenfassung der gefundenen Methoden zur Kodierung von Entwurfsmethoden und ihrer segmentierten Domänen für eine potenziell umfangreichere Erforschung generativer Lösungen in der zukünftigen Architekturmodellierung.

Das Fazit zieht schließlich einen synthetischen Überblick über die gesamten vier Kapitel der Dissertation und die darin entwickelten Aussagen. Sie beginnt mit der Abstraktion eines synthetischen Beitrags über die Idee der *intelligenten* Architekturmodellierung, bei der durch die Modellierung von Intelligenz selbst ein Weg aufgezeigt wird, wie die Vorteile der Berechnung in der Architektur weiter genutzt werden können, und andere generative Ansätze als die syntaktische im Bereich der Information und Kommunikation vorgeschlagen werden. In der positiv hoffnungsvollen Perspektive, diese Forschung fortzusetzen, werden einige Einschränkungen und Vorwegnahmen für die nahe Zukunft erwähnt, um bestimmte Gründe und perspektivische Anwendungen als neuen Ausgangspunkt neu zu definieren.

0.3 RÉSUMÉ (FR)

L'aspect probabilistique avec lequel nous pouvons nous saisir du monde et de nous-même est dorénavant d'une importance des plus limpides. Ceci est étroitement lié au fait que le concept d'information a progressivement dominé notre production des Idées depuis le 19e. Il est maintenant plus que temps d'embrasser et maîtriser pleinement de manière pervasive les modèles d' information et communication afin de construire des nouvelles bases de capacité, limites d'un nouveau genre à explorer. La prudence oblige de considérer cette affirmation sans la confondre aux points de vue positivistes, et tendre vers l'expression d'un sentiment positif dans les modèles que nous élaborons afin de nous observer et comprendre en tant qu' être humain intelligent tout en essayant de modéliser le monde qui nous entoure et nous inclus. Le paradigme informationnel, son approche probabilistique et inférentielle provient de nombreux domaines de recherche liés à la perception, cognition et representation de l'information qui, sur bien des niveaux, devrait fournir des approches plus contemporaines sur la manière de penser la modélisation architecturale, l'encodage des parties et leurs articulations.

Au travers du titre (*Neurodesign, Modeling with Neural Potentials*), le terme *potentiels neuronaux* (*neural potentials*) est duplicite: *potentiels* issu de la dénomination énergétique courante potentiel électrique en tant que vaisseau d'information à décoder, et potentiel en relation avec la notion de capacité contenue par cette information. La thèse présentée se constitue de trois chapitres, une conclusion et une annexe présentant les publications et productions de recherches. L' intention générale qui se reflète au fil de la thèse est celle d'exprimer la mesure tenue entre les résultats d'origine empirique et théorique qui s'informent les uns des autres sur l'ébauche de formes potentiellement nouvelles de la modélisation architecturale et de son encodage.

Le premier chapitre retient la forme d'une introduction étendue sur les bases contextuelles et positions prises au cours de cette recherche. Afin d'expliciter l'importance des circonstances particulières qui ont posés les arguments de fond de cette thèse, les parties qui le compose sont développées de manière apophatique, selon des notions clés qui se sont trouvées dépourvues d'une partie de leurs constituants, principalement au cours des deux derniers siècles. Le chapitre commence par une introduction générale sur les contextes identifiés, la structure de la thèse, ses méthodes ainsi que les parti-pris théoriques. C'est ainsi que la partie principale déploie les bases contextuelles de la modélisation de l'intelligence selon des descriptions apophatiques qui soulignent - l'obsolescence des centralités particulières dans la pensée scientifique après la crise de l'intuition du 20e, et les opportunités révélées à penser le calcul numérique en architecture (*Knowledge without Center*), - la transformation de la raison en rationalité puis sa réapparition dans une forme objectivée durant la même période (*Intelligence without Reason*), - la capacité des modèles de calcul numérique, à la fois dans leur incomplétude et leur complémentarité, en tant que forme de modélisation intelligente et potentiellement plus capacitante (*Computation without Universality*), - les modèles de calcul numérique traitant des théories représentationelles de l'esprit et la manière dont certains de leurs éléments suggèrent une voie d'appréhender les capacités cognitives humaines à donner valeur au monde selon un mode non-exhaustif (*Minds without Meaning*), - la quête sans fin dans l'association spatiale d'évènements de l'esprit et qui a mené à l'abondance d'idées sur la mecanisation du traitement naturel des symboles. (*Events without Places*), - l'aspect temporel grandement négligé de la modélisation architecturale au regard de l'esprit humain et la manière dont il se rapporte aux évènements et leur évaluation (*Articulation without Representations*).

Ces parties s'ensuivent d'une réflexion rétroactive et synthétique sur des travaux précédents et en lien, avant de résumer l'introduction contextuelle et porter la lecture vers le sujet principal de la recherche en modélisation architecturale avec des potentiels neuronaux.

Le second chapitre (*Modeling with Neural Potentials*) prend donc le sujet à corps et propose d'en développer une ébauche théorique. Ce faisant, il prête une attention selective à l'étendue de la gamme d'idées communes sur l'intelligence et la modélisation en logique, mathématique, informatique, science cognitive, philosophie, art et architecture. Certains concepts et positionnements personnels sont proposés pour de potentiellement nouvelles manières d'appréhender la modélisation architecturale au cours des parties qui s'ensuivent. - La première partie (*On Models and Modeling*) démarre ce chapitre avec un aspect plus abstrait et général de la modélisation scientifique et identifie deux types de modèles qui soutiennent la réflexion de manière complémentaire. - La deuxième partie (*On Cognition and Memory*) se penche sur la capacité virtuelle de la cognition humaine à produire du sens. - La troisième partie (*On Tokens and Beliefs*) présente des idées clés sur les dynamiques des valeurs informationnelles à partir des théories de l'information et communication et la compréhension de la vision en tant que technologie à part entière. Permuter ces idées à la modélisation générative architecturale lui offre ainsi une plus grande vivacité opérationelle en termes d'information. - La quatrième et dernière partie (*Architectural Modeling with Neural Potentials*) aggrège l'ensemble de ces développements dans un cadre architectonique et la modélisation pour contribuer aux idées du calcul, du génératif, et des articulations de manière progressiste. Enfin, le chapitre se termine par un résumé synthétique de sa contribution théorique principale au sein de la thèse.

Le troisième chapitre (*Experiments in Modeling with Neural Potentials*) reconsidère les réflexions précédentes de manière pratique et technique autour d'expérimentations qui traitent du modèle complémentaire d'intelligence à l'interface entre ordinateurs et la vision computationelle en cognition humaine (ou visual *Brain-Computer Interfaces*, BCI). Ce chapitre est divisé en deux parties principales: - la première partie (*Corollary References*), sert de revue initiale pour l'état de l'art de la recherche dans ce domaine pluridisciplinaire, et tout en identifiant progressivement les idées et méthodes clés par-delà des applications cliniques et d'assistance, elle catégorise et généralise les composants principaux depuis l'acquisition des données au traitement des signaux et leur décodage. - La deuxième partie (*Conducted Experiments*) implémente ces méthodes progressivement et s'attache à déporter des modèles existants de BCI sur la communication naturelle de l'orthographe des mots vers l'aggrégation de parties sur le mode visuel. Cette partie démarre avec la généralisation d'un modèle de référence connu (*P300-BCI Word Speller*) pour la discrimination visuelle et ses méthodes. Elle se poursuit avec une version adaptée d'épeler des mots pour générer des formes et examine les dynamiques potentielles de la signification encodée. Une troisième et dernière expérimentation enrichie la réflexion et développe un dernier modèle computationnel qui combine la capacité humaine à discriminer visuellement au sein d'environnements complexes et la capacité de l'ordinateur à générer des solutions probables en grande quantité au sein d'un vaste espace latent. Cette dernière expérimentation prend la forme d'une agrégation itérative de parties aux formes non-triviales et propose que le modèle ici développé permet d'approcher la modélisation générative architecturale sans à-priori syntaxique.

De la même manière que les chapitres précédents, celui-ci conclut par un résumé des méthodes définies pour encoder les méthodes de design pour une exploration potentiellement plus riche des solutions générées en modélisation architecturale.

En bonne mesure, la conclusion prend la forme d'une perspective générale sur la thèse et ses arguments. Elle démarre par abstraire une contribution à l'idée d'une modélisation architecturale *intelligente* à partir de la modélisation de l'intelligence-même, au royaume de l'information et communication, et offre une alternative de pensée aux approches génératives syntaxiques. Dans l'anticipation de poursuivre cette recherche, des limites et développements futurs sont précisés afin d'en redéfinir les bases et possibles applications.

0.4 ACKNOWLEDGEMENTS

Acknowledgements are of a proverbial nature. How peculiar is the event of an author found to be crediting, and thankful for, unexpected causes? However, I believe that acknowledgements occupy the role, in every consequent writing, not only to pay respect to a phylum of characters, but also to provide a glimpse at the backstage of writings. At what and who should be introduced, as judged consequential of the present work. I shall not break with the tradition, but will do so by showing my uttermost personal appreciation for what I believe has become a strongly personal and continued intellectual journey. Should its horizon, hopefully, never end.

Starting with the most immediate characters, I would like to express my sincere gratitude to the ETH *Architecture and Technology Fellowship Programme of Excellence* for having welcomed my research ambitions and fully funded this doctoral thesis for a time from October 2016 to 2019. To the *Institute of Technology in Architecture* (ITA) at the *Department of Architecture* (D-ARCH) for hosting this fellowship, and by providing constant exposure to the wide spectrum of research in architecturally-related technologies, which also became a constant reminder on the importance to maintain critical thinking at all times. And more particularly, to the *Chair of Digital Architectonics* at ITA not only for hosting me and supporting my research agenda from its arrival, but for having noticeably *cranked-up* the level of what I originally thought I could achieve during this time. It is henceforth hardly possible to picture this thesis without being there among my fellow colleagues and researchers, and particularly Pr. Dr. *Ludger Hovestadt*, Pr. Dr. *Vera Bühlmann*, Dr. *Elias Zafiris* and Dr. *Vahid Moosavi* for their feedbacks. By extension, I would like to thank *Ludger Hovestadt* for the supervision of this thesis and Dr. *Ricardo Chaviarraga* for its co-examination and insights. I also would like to thank Pr. *Frederic Migayrou* and Pr. Dr. *Jose Millàn* for their initial recommendations. My most profound, and too rarely expressed indebtedness to Pr. Dr. *Christian Girard*, not only for joining his recommendations for granting my PhD proposal, but for whom my esteem through the years progressively evolved from being a mentor, a colleague and a friend while never ceasing to provoke me for taking positions and formulating arguments. *Christian* remains in my mind the strongest figure of what an educator and intellectual friend ought to be. To Pr. *Philippe Morel*, as second supervisor and co-examiner. And whose capacity to summon the constellation of ideas which characterises his work on a theory of computational architecture always generated my uttermost intellectual respect and deferance. Following the same path of acquaintance than *Christian*, *Philippe* appeared to me, through the years, as representing what a thinker of the contemporary should be doing. Holding that thought, arises the recollection of the comments of Roland Barthes about the *inactuality* in the second *Consideration* of Friedrich Nietzsche. My initial reflections and experiments about this work began while studying and teaching alongside them, and would not have been even imaginable if not thanks to their benevolence and active support.

In different latitudes, some would name it perseverance, or obstination. Bound to this particular period, stand two dear friends from completely different domains but who joined their trust and support in introducing me to the field of neuroscience and brain-computer interfaces (BCI) almost 10 years ago: Dr. *Fabien Lotte*, who helped me throughout the first BCI workshops, and Dr. *Leslie Ware* with the introductory art projects I conducted. I tend to believe that it must have taken a great deal of hope and kindness to foresee potentials in what most would have called then a fantasy project. As we dive deeper into personal gratefulness, we are now reaching to the dear trinity of women who raised me for about a half of my current life, my grandmother *Marianne*, my mother *Annie*, and my sister *Nolwenn*, and who taught me indirectly that the only belief which was worth sticking to was the one of nurture. Indulging me in that regard, the everlasting patience and kindness of my current partner in life, *Maria*, never ceases to elude me and cannot find an adequate enough gratefulness. Last but not least. As it has been so rare in the past years and while constantly raising expectations and efforts, I would like to especially thank and indulge myself for constantly going forward and building the exciting horizon of what still remains to become of my academic and professional life.

CONTENTS

INTRODUCTION 1

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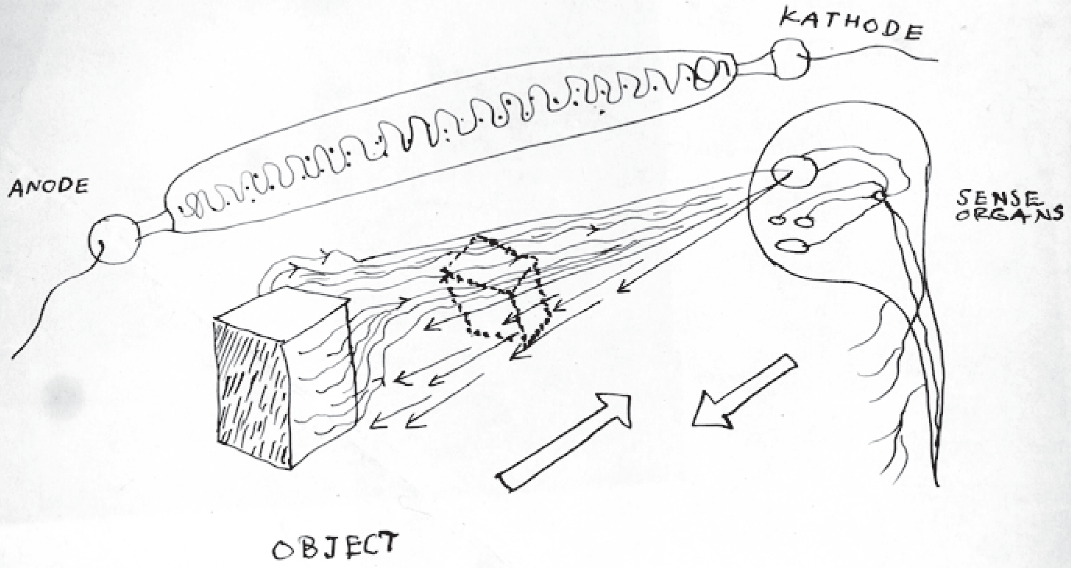
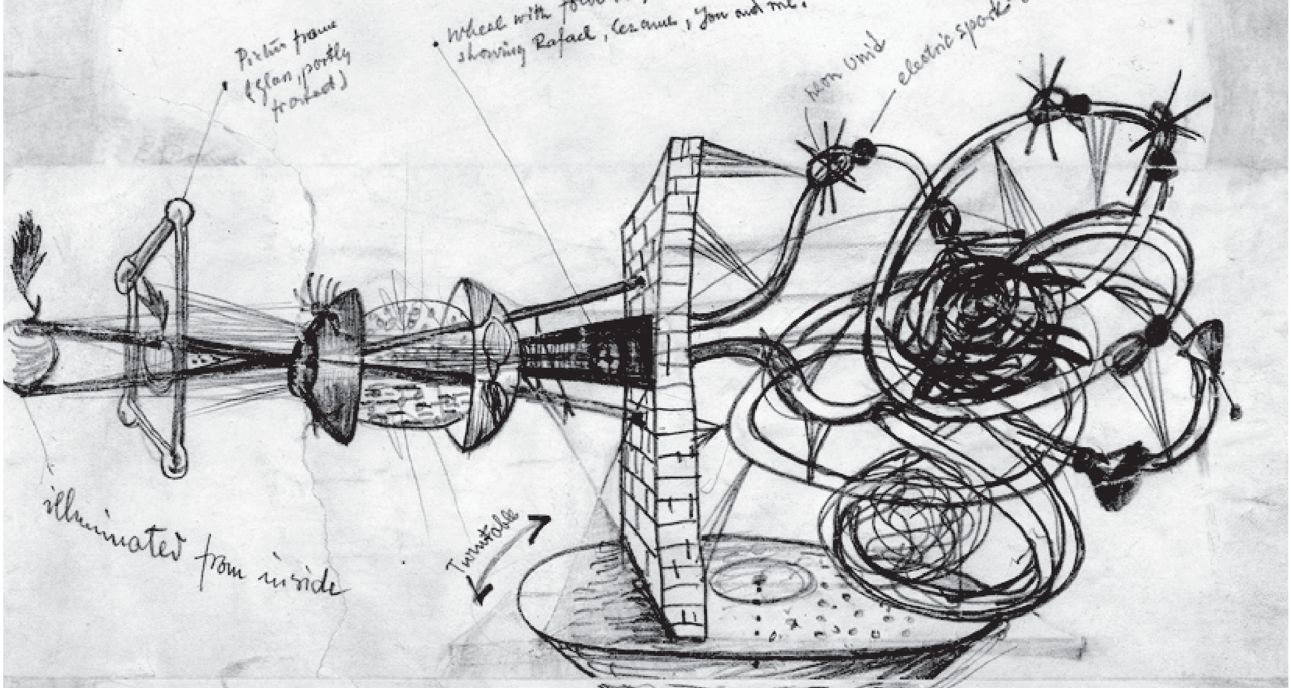


Do we see in a two-way system?
or only by reflection?
Or do ray's from the Eye-Brain
meet (so to say in a conductive VACUUM) the
generation of light (-heat) from the Object and
unite in order to produce an illusion of the object?
Why is the vision always smaller than the Object it sees?



1.1 PREFACE

One can easily agree, nowadays, with the fact that, apart from a short-sighted 19th c. tradition, which entertained the invention of scientific disciplines (along with expertise) towards the end of the Enlightment, and saw the birth of Romanticism (Stichweh, 2001), architecture does not sit quietly as a discipline (C. Girard, 1986; Piotrowski and Robinson, 2001), but rather performs within a skillful summoning of epochal thinking, or otherwise known as bodies of knowledge. And in order to perform within a coherent body for the 21st c. , where digital literacy is at stake, a chosen hosting point for this research was found in the significant efforts done since around the past decade at the chair of CAAD ETH Zurich to redefine ***what is articulable digitally today***, or Digital Architectonics[1]. At the core of this work, lies a certain way to constitute * such body coherently. By learning from symmetries throughout the *History of Ideas*, the chair formalised a dialectic spiral with no specific periodisation of History, but cultural axes of symmetry, in reference to Gustave René Hocke (Hocke, 1957) and Eric Voegelin (Voegelin, 1956), from which the contemporary Digital may then reflect with the whole Renaissance (Hovestadt and Bühlmann, 2014). The present research took great lessons from these methods and, while not entirely fused in its tracks, its general intent aims toward a sympathetic point while looking for means of articulating things of our contemporary world.

Descriptions of the world in architecture, or more precisely, the understandings on perception of *things-in-the-world* have always remained a discontinuous but recurrent and underlying idea since intricately linked with later considerations towards these very things for architectural interests. Later being emphasized here as ***an afterthought***, a succeeding event of some sort. * As if the *modern condition* described by Hannah Arendt (Arendt, 1958) would have taken the shape of a self-realizing prophecy in architectural thinking. Such historical discontinuities, yet synchronous with epochal thinking (Mallgrave, 2010), might reflect as well a history of causal assumptions on the *meaning*, or saliency, of a perceived event.

As far as we may recall, first anatomic dissections run by Alcmaeon of Croton during the Pre-Socratic period (Gross, 1995) were carrying the premises of embodiment of reason which held until late Europe Renaissance (Clarke, 1963). The re-emerging individuality of the *humanist man* as the centre and measure of all things, as a direct influence of the teachings on *relativism* by the Sophist Protagoras, was integrated in architectural thinking during Renaissance Humanism as a double analogy occurring between the human body and the building (Alberti, 1485), or the generalized object of perception and design. For a short time, the Baroque period replaced in reasoning and representation the idea of a central figure with the *multiple*, manifested by the oval figure and the open form (Wölfflin, 1888). But did not pervade during the transition towards Enlightenment and the scientific dominance on views of the world. This age of *Reason*, dominated by the c*artesian doubt*, the empirical basis of knowledge of the world (Locke, 1689a), and a clear separation between the mind and the body left the later, as well as any other thing, in the realm of matter as an object of science and conveyed architects such as Claude Perrault (Perrault, 1683) to the idea that harmonic values were physiologically grounded (Mallgrave, 2010). Yet leaving higher cognitive processes of judging *Beauty* to the indisputable task of the soul, his practical statements echoed in tradition of the *anatomist* thinkers such as Alcmaeon of Croton and Aristotle or the closer Leonardo Da Vinci. Probing physical grounds in search of reality were by then already underlying in architectural discourses but still lacking the modern notion of time as an active process of writing events in history and how they come to

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[1] Here, it is understood as a whole body of work the period, related through writings, from *Beyond The Grid: Architecture and Information Technology; Applications of a Digital Architectonic* (Hovestadt 2009), to *A Genius Planet, Energy: From Scarcity to Abundance – a Radical Pathway* (Hovestadt, Bühlmann, Michael 2017), and current texts up to 2019.

mind. With the british Empiricism and the aesthetic theories on the Picturesque, appears the transition from *Beauty* to *Taste* (Knight, 1805). As well as the negation of the humanist double analogy in architecture (Burke, 1757) according to the stated *inductive reasoning* of David Hume (Hume, 1748, 1757). With the apparition of the picturesque assumption that primary sensations would be improved by later associative ideas, come the founding understandings of visual cognition as a deep temporal process.

One might foresee already, through this extended and selective storyline, the displacement of cognition in architecture from space, to matter, to time. Additionally came another influent epochal idea on the limitations of reason by separating perception in the phenomenal world, from pre-structured percepts of the noumenal one (Kant, 1781a, 1790). Leaving, by then, architecture to nurture in the dressing of the former (Semper, 1860). In the following developments of physiological psychology (W. M. Wundt, 1874; Stumpf, 1873) and their direct assertions to architecture (Woelfflin, 1886; Vischer *et al.*, 1994; Göller, 1888), we can observe, a critique reminiscent of a late baroque, an exhaustion in the production of forms. Similarly, in mathematics, physics and information technologies join an epochal marker at the end of this intuitive apperception (Hovestadt and Bühlmann, 2012) which seem to remain actively amplified by philosophy of cognitive science (Fodor and Pylyshyn, 2015) and computer science (Brooks, 1991). A late Gestalt (Koffka, 1927) reaffirmed that cognitive activities would go far beyond fully conscious, and temporally graspable, processes in the unconscious; leaving a reading of the writing of history as equally ungraspable in its entirety. From then on, it seemed that architectural interpretations of cognition would follow-on the tracks of phenomenology (Rasmussen, 1964; Pallasmaa, 1986; Vesely, 2006). And even reassess the humanist analogy between human physiology and the built environment (Neutra, 1954; Eberhard, 2009). An experience, by filiation (Husserl, 1936; Heidegger, 1927), clearly disengaged with the contemporary understandings of capacity in reality, and our relations with things-in-the-world.

This missed opportunity can be seen in relation with the cybernetic age and when the mechanization of knowledge took a significant turn (Wiener, 1948, 1950). In opposition with the contemporary development of embodiment of Maurice Merleau-Ponty (Merleau-Ponty and Carman, 1945), while a clear occlusion was made on architecture to remain experienced in space and matter (Perez-Gomez, 1963). Yet during the same period, with the increasing understanding of electromagnetism and its signs becoming messages in control and communication technologies, new ways of encoding events emerged in cognitive science and technologies, by sensory transduction, in the form of *Event-Related* and *Evoked Potentials* (ERP, EP) (Vidal, 1973, 1977; Donchin, 1979) in electrophysiology, and specially applied to neuroscience. The active development of interfacing the brain (as a primary cognitive synthesis field of physio-psychological and cultural phenomena), and machines (as encoding and inferring mechanisms to assess beliefs and models of cognition of the world). What Brain-Machine interfaces (BMI), or Brain-Computer interfaces (BCI), offer today are a new architectural ground for this debate. A ground not necessarily anchored in the phenomenal world. By bringing back our evolutionary understandings of knowledge in a hybrid and dynamic system. Such inferring (Peirce, 1883) interfaces, enabling dynamic loops by hebbian plasticity (Hebb, 1949) establish the context of this present research. Grounded in time and frequency to infer on an architectural discourse of the *precedent*, an active and dynamic understanding on perception of things-in-the-world.

This is from where this research will start, reflect, articulate questions and problems. And hopefully, contribute to the literacy of architectonics, going after the digital, the computational and the modeling of intelligence for new potentials.

1.2 A THEORETICAL STATEMENT

In any formalistic account, architecture and its modeling are intractable. And that is probably due, despite all efforts, to the role that heuristics take in that task exhibits an unparalleled power compared to stochastic methods. Instead of seeing this as an issue, we foresee an opportunity. This thesis is thought to be, and to be thought, as pertaining to a computational project. And, in the search for synthesis, also as a reductionist one. That is to approach the topic of architectural modeling from a computational perspective which should regress inversely proportional to the amount of sophistication of our knowledge of the world and its reflective purport in architecture. It should be clear that the more one knows of the world and oneself, the more one should reduce the amount of necessary operations in order to make room for novel capacities. This takes shape in an effort to prototype a technology that emulates such capacities. We cannot see how a disciplinary and autonomous claim of architecture would help in that endeavour and choose to rather focus on producing a synthetic understanding of the modeling of intelligence in the search of complementarity, corollaries and untapped potentiality. Consequently, This thesis is indivisible either of its theoretical or experimental investigations. Neither purely theoretical nor technical, it should be seen in the terms of the times, as a formative expertise. One that touches the question of intelligence and its capacities for modeling while necessarily embodied into empirical studies and framed by theoretical domains. Although it does not claim any of these particular expertise, it aims to advance both as a whole and to adequately address technology in and for architecture. Most theoretical standpoints of our times tend to be drawn from an ethical background. Stemming from socio-cultural peer pressures and group behaviours to reinforce the value of arguments in favor of the necessity of immediate causes. But how scarce are the intellectual contributions borne out of consensus? Capacity, in its widest descriptions, is the seed of invention. Which in return brings potent answers to actual necessities and not the way around. It must be made clear that what follows is in the search of the former.

1.3 THESIS STRUCTURE AND METHODS

Along the redaction of this thesis, a few points of conduct and methods have been established to structure its reflection and restitution. This took the shape of a tripartite redaction. The introductory chapter grounds the research on a larger legacy of *intelligent* modeling. The following chapter prototypes a vocabulary and means to articulate it amongst the aggregated and transdisciplinary body of knowledge in the perspective of architectural use. The third chapter describes litterature review and experiments with existing techniques of interfacing human brains with computers (BCI) for progressively drifting design methods for architectural modeling. Provided here as a linear succession, they have been conducted mostly concurrently over the course of the research and kept informing each other on the way in an organic fashion. The expressed efforts for coherence and synthesis start immediately hereafter the present remarks. Conducted experiments have been following state-of-the-art and stable BCI literature to comprehend the necessary trade-off between theoretical arguments and practical operativity. Accordingly, the robustness of found methods was put to test with the constraints of the physical environment. Practice and theory, abstraction and empirical evidence take part in an endless circle for reasoning. We aim to build knowledge upon such structure. The thesis gathers technical research papers and theoretical writings from varied views in the perspective of arranging a choir of voices which should tune in the common goal of what is modeling and what it has to do with architecture nowadays.

More formally in the body of the text, we refrained from reproducing lengthy citations or demonstrations for the sake of synthesis, and which are generally found elsewhere than in the present research as a form of placeholder to justify reported arguments and largely disengaged from personal contributions to emerge. Most of the references used here are rather introducing each section for a synthetic interpretation of the relevant arguments they represent. Left to the appreciation of a seasoned reader, the efforts put in articulating ideas and appropriate references favour the spatiality of the task at stake rather than a redundant analysis which would be better found in the scope of other research of the disciplinary kind. Reading can occur linearly through the body of the text and its structuration. However, each chapter can also be read independently. Many references across the sequential structure of the thesis have been made to allow for a differential and more toplogical way of reading as well. Summaries are provided at the end of each chapter to momentarily bind the domain of reflection in a synoptic perspective. They play a commentary role and are to be considered complementary to every each developed subsections. A final overview of the conducted research and its future perspectives is nevertheless provided at the very end.

> *[...] without assymetry or desiquilibrium - there is no irreversible, no chain emerges, and time is unknown. In a strict sense of the word, commensality is eternal.*
>
> *- Serres, Michel, 1997, trad. 2007, The Parasite,*
> *Univ Of Minnesota Press, Minneapolis, p183. -*

1.4.1 *Knowledge Without Center*

In an opening chapter of his book The order of Things, Michel Foucault took upon an ontological investigation of the painting *Las Meninas* by the Baroque painter Diego Velàsquez (Foucault, 1966). From the analogy of the *Classical* representation understood as an open and virtual space upon which epistemic assumptions may be drawn, and to later define *modernity* in scientific thinking, he recalls the general naturalisation of centrality in *epistemes* and argues for its obsolescence. Comparable to a *copernican* revolution, the natural centers of the time represented by *Sun* or *Man* had, from then-on, disappeared. Which led to the epistemological consequence that *meaning* would have to be sought anew and amid knowledge, its simultaneities and dimensionalities; as a permanent archeology of the *contemporary*[2] . And as to the painting (see Figure 1), its superposition of modes of picturing the relationships between the viewer, the painting itself, and the world in an all-encompassing fashion embodied a perpetual generator of beholder responses depending on the way to look at it (Alpers, 1983; Carr and Bray, 2006; Chrisley, 2008). This constituted a powerful metaphora for what not only may qualify as a masterpiece of art in the eye of many, but also what we might expect from every human production which may attain a certain level of abstraction, despite its physicality. ***A general capacity to articulate sense***. Should it be numerous, and drawn from many centers. *

Similarly, architects ought to reframe the contemporary conditions of what is *articulable digitally* nowadays in order to draw sense out of it. Then, such potent and abstract understanding requires to distance oneself from immediate effects that *Information and Communication Technologies* (ICT) superimpose over the physical world, and rather intend a synoptic observation of the transformative causes. The direct opposite being a general and common mistake, drifting away from contemporaneity by looking at such effects in a more immediate and tangible fashion, and which too often punctuates the history of seminal architectural thinking up to our time. As a recent example of such symptomatic endeavor in direct link with the history of ICT, the late 20th c. symbolic crisis throughout the works of Charles Jencks, Robert Venturi et al. (Venturi, Scully, and Drexler, 1966; Jencks and Baird, 1970; Venturi, Izenour, and Brown, 1972; Broadbent, Bunt, and Jencks, 1980) can then be read here as the passive analytic approach of urban manifestations from a rather ambiant informational phenomena (Cutellic, 2016). While a rich intellectual production was at work in the development of ICT, these architectural foci were instead on its immediate and tangible consequences over the reading of the city. The findings then become consequently positivised as it may only lead to a *necessity* of rethinking architecture after the digital, instead of thinking about the *capacity* of architecture in articulating it. Because issues might arise by looking for such capacity of articulation directly from the notion of the *digital* itself, as it encompasses a certain kind of representation, or effect, of information that is a *code*, and was already understood as-is in foundational theories of ICT(Shannon and Weaver, 1949).

While in its most architecturally relevant aspects, a code may very well constitute a correlate of *geometry* (Bühlmann, Hovestadt, and Moosavi, 2015a), the same potentials cannot be found about the articulation of information, or *encoding*, as it lays within a much larger informational framework of transformations which would rather be constituted by the *computational* and its capacity to deal with models of information and its processing, prior to

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[2] Contemporary is to be understood here as an anachronic relation to one's own time by seeking its peculiarities. By doing so, it eventually takes the form of an archeology of what makes such peculiar points relevant from an actual epoch. It is no coincidence to find such terms in Foucault's own writings. And a most compeling and summarized definition of such contemporaneity may be read through Giorgio Agamben's inaugural lecture at IUAV, Venice, Italy (Agamben, Giorgio. 2008. *What Is the Contemporary? "What Is an Apparatus?" And Other Essays*. Stanford University Press. pp39-54).

Figure 1: Painting of *Las Meninas*, Diego Velàsquez, 1656, Museo del Prado Madrid. Source: link

representational states (Piccinini, 2008). From a current counterpoint, it might still appear convenient and all-encompassing to identify, as prominently developed by Mario Carpo, that a digital condition is actively transforming architectural modes of thinking and production (Carpo, 2011), and constitutes a point of contemporaneity, but while reminding a corollary criticism of Peter Galison, one can see that, yet again, it would not draw out from a latent and obstrusive modern technological positivism (Galison, 1990), and rather lead the way towards such traditionally constrained formalisations. Followingly, most contemporary accounts of computation in architecture tend to employ ideas about the computational primarily for design and formalisation purposes and can generally be framed, as summed up by Philippe Morel, either as a *neo-rationalism*, or *expressionist humanism* (Morel, 2019). While the former intends to justify their design by an economic and mimetic approach of computerised natural phenomena, the later would intend to systemise variance in a formally represented continuum. All in all, neither may hold the promise to account for informational modes of articulation at the level of abstraction that computation may really offer for architectural modeling. It could be reasonably argued that every architectural design is aiming to purport these ideas at miscellaneous degrees. But then becomes particularly abstruse and superficial whencesoever reduced to formalisations as a prior account of meaning. As a result, and because the scope of this research is touching on the general notion of intelligence and its modeling by intending to layout architectural design correlates, we will find more appropriate to ***start by the rich history of the encoding of information (ie. computation) rather than the sub-history of its coded reproduction (ie. digital)***. By then, the numerous centers to construct this research should appear more potent. *

As developed at length by Ludger Hovestadt and the chair of *Digital Architectonics*[3], the potentials that 21st c. architecture might peruse from computation should rise from higher levels of abstraction (Hovestadt, 2015). A general reading of both the past century and the one in which we are engaged, strongly suggests for computational accounts of architectural modeling, to not be pursued with formal logics as an a posteriori layer or passively executional mean, an *afterthought*, of architectural thinking. Wether they depend themselves on informational models or not, could not constitute any stable ground for prospective contributions. Instead, one should consider the all-embracing capacity that computation has to offer about the very idea of modeling and its inferences, its intricate relations with information, its mediated interaction between the world and ourselves. If design, as a narrative component of architecture, may be seen as a tangible fragment of reality and which plays its role in the narration of the world, it also defines the particular ambition of such fragment, or object, to become meaningful (Hovestadt and Bühlmann, 2014). And in such perspective, architecture may find its design narratives in the planetary phenomena of what is now commonly called *Big Data*. Considered as a *jungle of primarily intellectual abundance*, the whole digital archive of the world becomes a ground to engage with its imprint, in symmetry to Renaissance, and probe for the invariances of *worldly* objects (Hovestadt and Bühlmann, 2014). However, artificial intelligence and big data are not synonimous endeavours and immanances do not necessitate vast quantities of information but depend primarily on dimensionality (Riemann, 1868). In a way, the probabilistic principle in tackling uncertainty in this emergent phenomena from an ICT perspective was to be able to produce objects of reasoning from a distance. Structured data becomes meaningful parts in a world of objective reason and where algorithms play the role of articulations. This would trace a general understanding of what we could already call a form of digital literacy.

What was commonly called a *crisis of intuition*[4] at the beginning of the 20th c., or *intuitive apperception*, found in physics, mathematics and ICT (Hovestadt and Bühlmann, 2012), led to an externalization of reason by rationality in the modeling of intelligence and its capacity to produce meaning through probabilistic means. Giving the immediate understanding that objects are to be produced, not revealed. A paradoxical externalisation of reason to absorb its nature. And which provided for a reading of all 20th c. infrastructures to have become probabilistic projections of nature. However, as we now have access to both abundant amounts of data upon which to build new immanances, as well as the models to produce probabilistic objects, we must not seclude that, while the history of finding purposes in the representational content of architecture is being joined with the modeling of intelligence, the externalisation of reason which permitted to build these news means for digital exploration did not exclude any natural phenomena but rather internalised them. We became ourselves sources of digitized information as well as the perpetual mirroring of our objects, including the one of intelligence. The centered man did not disappear exactly. But, it diffused its centrality and engendered numerous points to consider in the 21st c.

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[3] A synthetic overview of the practical and theoretical journey operated by the research group, formerly known as the chair of Computer–Aided Architectural Design, from the end of the 20th c. may be read directly throughout the synopsis of their website, as well as their bibliography. See : link, as well as: link and: link

[4] An event, moreover, which superseded the previously mentioned symbolic crisis in architecture by its time of occurence and general impact.

1.4.2 *Intelligence Without Reason*

A particular aspect of the scientific modeling of intelligence during the 20th c. and what it is today, has to do with how it dealt with the notion of *reason*. Or should we say, its transformative abduction. It becomes particularly clear while observing the philosophical conceptualisation of reason operated during late Enlightenment, and the subsequent rise of a Modern *rationality* expressed through the development of algorithmics in computer science (Berlin, 2011; Lemov *et al.*, 2019). Bearing witness is the seminal *Theory of Algorithms* of Andrey Andreyevich Markov (Markov, 1954), stating algorithmic desiderata funded on the rational grounds of *definiteness*, *generality* and *conclusiveness;* and for which human reasoning was rendered absent. As a prior to this pivotal moment of the formalisation of modern computation, the first attempts to convert reason into rationality by cumulative philosophical efforts, among which Gottfried Wilhelm Leibniz' De Arte Combinatoria (Leibniz, 1666), Pierre-Simon Laplace's Probabilités (P.-S. d. Laplace, 1825) or Nicolas de Condorcet's Probabilité des Décisions (Condorcet, 1785), were first deprived of their original content regarding a certain mindfulness of reason, through the project of creating a universal and reasonable calculus, to then be later reemployed in, mindless, rational terms. For Leibniz, the *Calculus Ratiocinator* and *Characteristica Universalis* (see Figure 2) were part of a wider project of an alphabet of human thought (Leibniz, 1903, pp. 153–157) (Couturat, 1901), and foreshadowed what would later become *Gödel's Coding* (Russell, 1945). For Condorcet's educational project, calculus was a guarantee of intellectual clarity, exactitude of the mind and political autonomy, by providing justified beliefs and self-evidence (Marty and Amirault, 2020). Through the repetition of arithmetic rules, studying calculus would enable the formation of ideas, judgements and reasoning without leading to mindless automatism by sets of formal rules (Condorcet, 1794). By then, a clear order was drawn about the human intellect and its productions. An even clearer example of such effort could be found in Kant's Critique of Judgement (Kant, 1790), and where the genius is providing for the values of fine arts (Kant, 1781a). In that humanist tradition, reason was then considered as the highest of intellectual faculties drawing upon all others such as memory, understanding, judgement and imagination. Mindfulness was therefore an essential component of reason because of its value regarding the human discrimination of inferences, judgements and decisions in the face of complexity and contingency (Lemov *et al.*, 2019).

One way to understand why certain aspects of reason were first rejected and then reinjected into rationality is through the broken continuum regarding the idea of *certainty* which drove Medieval Latin Europe and was elevated as the summum of epistemic meaning in science (Pasnau, 2014). In that tradition, natural philosophy was driven by the aspiration of certainty and universal knowledge from the human mind. But this continuity finally was exposed as broken when calculation, which was then considered as one of the highest human reasoning faculty, became reliably mechanized and took ample demonstrative proportions as in Charles Babbage' s *Difference Engines* (Grier, 2005, pp. 41–45). Such endeavors were then clearly operating on the establishment of mechanical procedures for the transposition of both manual and mental labor in modern calculus driven by a project of economic rationalisation started earlier. For by the end of the 14th c., the distinction appeared between a singular model of certainty and one of rules, for which the later became more practical and procedural for the development and reproducibility of grammar and mathematics (Lemov *et al.*, 2019). Hence, a growing centrality of rules for what accounts to be rational rose to modern scientific efforts to demonstrate a universal rationality without judgement, discretion, reflexion and reason as traditionally defined, but only by its procedural generalisation as synthesized in John Von Neumann and Oskar Morgenstein's Theory of Games and Economic Behaviors (Von Neumann and Morgenstern, 1944), which served as a foundation for the modern computerisation of intelligence and the early cybernetic project.

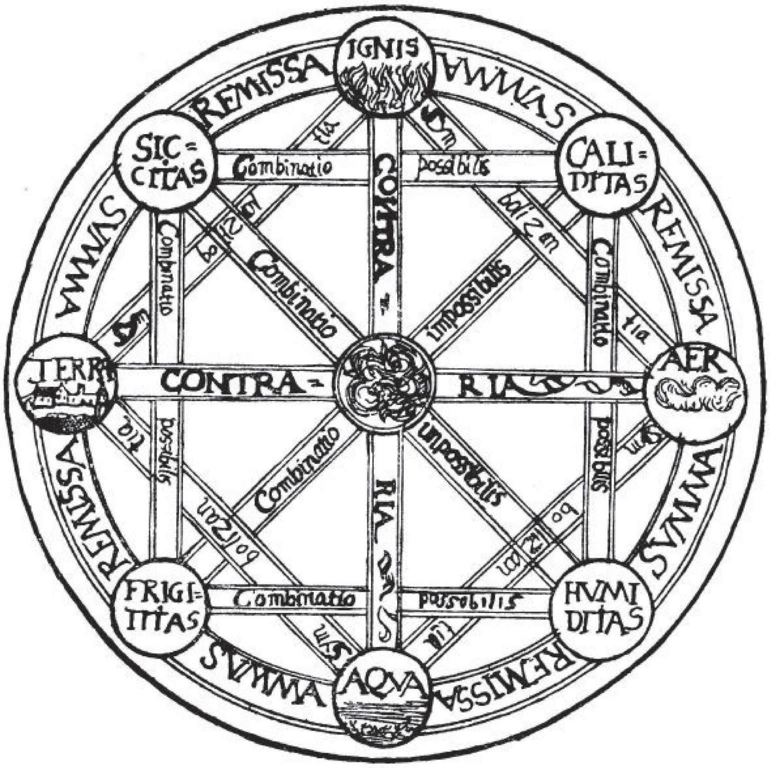

Figure 2: Illustration of Leibniz' diagrammatic reasoning in *De Arte Combinatoria*, 1666. Source: link

However, as such models became themselves the rule in artificial intelligence over the second half of the 20th c., they also emphasized their epistemic issues and implicitly reappraised the classical notion of reason at the rescue (Brooks, 1991). With the growing concern that contingency, complexity, chance and uncertainty were becoming the main vectors at work in the post-modern world, the critical tasks of interpreting and situating contextual information questioned the initial cybernetic project of *Computers and Thought* (Feigenbaum and Feldman, 1963). Similarly noticed alongside the modern developments of rationality, also evolved the ones of *objectivity*, and which jointly reappraised the idea of judgement about digital depictions and their capacities for variable interpretation (Daston and Galison, 2010). A certain ontological complexity seemed to have then been growing and stacking up from the 18th c. on, in objective depictions of the world, and which marks are still apparent nowadays in computer science (Halevy, Norvig, and Pereira, 2009). Around the first half of the 18th c. , probability theory started to spread from a rational approach of the unreliable experience of the world, (Gigerenzer *et al.*, 1989a; Hacking, 2006) and *reason* started its transformation into *reasonableness* to install the idea of rational belief in an attempt of taming chance (Hacking, 1990). However, the by-then still dual presence of both subjective beliefs and ojective frequencies found in classical use and thinking of probabilities as previously mentioned, promptly became antagonized in philosophical and scientific programs (Daston, 1995) such as in John Stuart Mill's *System of Logic* (Mill, 1843), or George Boole's *Laws of Thought* (Boole, 1854a). And the rationality found in the mathematisation of a greater number of individuals through the administration of social physics and the instrumentation of statistics and methods proved to be more stable grounds. The *analysis of variance* developed and diffused through Ronald Fischer's *Design of Experiments*

(R. Fisher, 1935; Gigerenzer *et al.*, 1989b) had great influence over the idea of judgement and the capacity for indeterminism that individuals were presupposed to have prior to that period (Gigerenzer *et al.*, 1989c).

The deterministic framework in science carried great weight throughout the last two centuries, and when entered the scientific field of experimental psychology to reconsider the modeling of cognitive processes of thought by computerization during the *inference revolution*, it led to the standardisation of human choice under uncertainy, or the *standard picture* (Samuels, Stich, and Faucher, 2004), as a novel form of objectively explainable reason which may provide for rational accounts of subjective reason for human individuals to engage with the statistical dimensions of the world. The identified irreducibility of the dual compound objective/subjective in probability theory by Rudolf Carnap (Carnap, 1945) resonates with the Eclipse of Reason of Horkeimer (Horkheimer, 1947) in the late 20th c. The place of humans in the great project of modeling intelligence seems to have come back to a more inclusive approach where choice is central to human participation and emulation, and where objective reason has casted away its prior naturalistic ideologies.

1.4.3 *Computation Without Universality*

In tradition to modern rationality, many contemporary thinkers involved in both scientific theoretical and applicative andeavours have pursued the idea that all phenomena of the universe may be considered as products of computations, and therefore have been attributing a universal property to the concept of computation itself. For example, the collective project of *computationalism* in cognitive science and the philosophy of mind became the frame for a vast array of tentatively exhaustive descriptions of cognitive processes through computational models (Piccinini, 2012). And another analogous project called *digital physics*, started by Konrad Zuse (Zuse, 1967), simply encompassed the universe as a computer based on the physical tractability of algorithms (Schmidhuber, 2000). Following that train of thought, one could argue that computation was given the character of *universal graspability*. Leaving not a thing untouched by, or beyond the grasp of, computer models. The universality thesis is mainly rooted on the *Church-Turing Hypothesis* (Church, 1936; Turing, 1936; Rosser, 1939). It states, in a fairly simple but powerful way, that any computable function can be computed on a Turing machine, and algorithmic depictions of the physical world are possible, and possibly exhaustive. Among the plethora of protagonists, one could name as an example one of the most influential and popular in architectural theories of computation in the contemporary period: Stephen Wolfram. He developped his *Principle of Computational Equivalence* (Wolfram, 2002) in order to reframe complex natural phenomena with analoguous and mathematically tractable mechanisms. It would seem an a priori tempting thesis for architectural discourses to adhere to. Since it proposes a graspable and operable framework for both general and particular complexities (see Figure 3). But since computation is constantly being recalled to its limitations and responsively evolving, it might be more appropriate to think about ***computation as a form of incomplete but consistent scientific modeling rather than an all encompassing framework***. A scientific *demon* in that case[5] would be opportune. Helping to understand where to probe for understanding beyond its threshold.

That is somewhat an argument processed through the dialectisation of *computation* and *computability*, and the redefinition of mathematical *consistency* by logics, philosophy and mathematics. For which the works of Kurt Gödel, and most specially his *Incompleteness Theorems* (Gödel, 1931) may be taken as central. Prior to Gödel's Theorems, mathematical consistency was directly linked to proving a statement to be True. The main thesis based on *logicism* can be represented through the influential work of Gottlob Frege (Frege, 1884) until the beginning of the 20th century. By that time, such foundation changed its ground through the developments of modern logics and the work of Bertand Russel (Russell, 1903), by showing that True statements may not have a Proof, and verbal paradoxes may exist in mathematical formalisations while remaining consistent. This was later known to be named the *Russell's Paradox* and followed extensive developments in new mathematical foundations with symbolic logic, in collaboration with Alfred North Whitehead, in the trilogy of *Principia Mathematica* (Whitehead and Russell, 1910, 1912, 1913). In the midst of that change, the *Incompleteness Theorems* demonstrated the significant gap between *Truth* and *Proof*. And where *Proof* could be formalised by axioms, otherwise known as *Gödel Coding*, or *Numbering* (Gödel, 1931; Nagel and Newman, 1958), and computed in order to produce such truth from unproved statements. To understand how sounding such idea became for the advancements of mathematics and logics, the most influential mathematician concerned by the notion of universals through formalisations at the beginning of the 20th c., David Hilbert, wrote a set of 23 prominent problems to solve (Hilbert, 1902). And among which the 2nd was about proving axioms of arithmetics to be consistent. In the previous framework, every *True* statement should be provable. But Gödel's converted the necessity of the proof into axiomatisation. It resulted that a consistent mathematical system

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[5] For a more detailed explanation on the capacity and interest of the model of demons in scientific thinking, see 2.1.1

could not prove its own consistency because of its lack of t*ruth*. Henceforth, a foundational emphasis was put on believing in the axiom, the *coding*. What would shape the formal-linguistic perspective of later mathematical notions of computation such as *Lambda Calculus* (Church, 1932) or *Logical Computing Machine* (Turing, 1936), were precisely about dealing with the notion of *computability* and its limits through such approach (Longo, 2020).

Figure 3: An example of automaton's *Rule 110* of Stephen Wolfram's demonstrations of modeling computational pendants of complex natural behaviors. Source: link

This particular condition, instead of its consequential technological developments into the universal thesis, led to the concurrent understanding that a logico-mathematical comprehension must reach beyond purely computational actions (Penrose and Gardner, 1989), and non-computability is a useful feature of thinking (Penrose, 1994). The resurgence of non-computability is equally based on two kinds of evolving reflections in cognitive science and physics, where two levels of behavior are irreducible to each other : *quantum* and *classical* (Aaronson, 2013). And non-computability plays a role between both worlds when particular ideas such as *measuring* comes into play (Penrose, 2000). This particular threshold, boundary of understanding, does not necessarily mean that they could not be formalised by logics and mathematics to be included in computational models (eg. Hilbert's 10th problem shows that certain mathematical problems may be non-computable). A more immediate and contemporary approach to that idea, also in tradition to the development of uncertainty and probability in mathematics may be seen in the global efforts of Karl Friston of *predictive coding* under the *free-energy principle* and which considers that some form of computation must happen as a judgement under uncertainty at some levels of abstraction of mental processes (Friston and Kiebel, 2009; Friston, 2010, 2012). But from single neural cells to larger populations and cortical regions, a correlate is yet to be found (D. Williams, 2020). What is important is that ***some phenomena can only be partly encompassed with our predominant models and their boundaries are the most contemporary, crucial aspects, of them***. As developed by John Searle in his consciousness argument (Searle, 1980, 1990), computation drifted and acquired ambiguity while trying to make intrinsic epistemic claims, while remaining ontologically subjective. However, a computer would be absolutely useless without the capacity to interact with the world. Wether or not it understands it, its modeling does not fit perfectly without uncomputable interpretations. So the incomplete, but coherent, definition of computation is somewhat what makes it capacious and useful. *

This is different to say that the intractable part of computation is of natural character, and to say that the real capacity of computational power is its incomplete character. While the former would realise the same conceptual mistake by reassessing the universal argument, the later would simply admit that incompleteness is a necessary condition and justification of computation. The syntactical definition and tradition of computation makes it powerful but to the limit of its concept which is marked by the exclusion of consciousness and other non-computable phenomena. Another remark can be made about the psychological significance of a computation. As emphasized by Leibniz, significance arises from a difference between later and prior information in computation (Rodriguez-Pereyra, 2014), the information resulting from a computation is the difference. But while a computer is perfectly capable to produce one, its significance remains out of reach. And as defended by Giuseppe Longo, a consistent distinction must be sought in computational modeling between the formalisation of information and its signification (Longo, 2020). Something that is not mathematically tractable can be in communication with a computational model.

1.4.4 *Events Without Places*

In the long history of sciences physiologically anchored with the brain, it is possible to conceive of the theories of localisation as being applied to the whole and then to increasingly smaller parts, to later eventually dissolve into abstract boundaries. From the heart/brain dispute of Antiquity for the seat of the soul, to cortical localisations of functional units in the 19th c., and current post-phrenological models of *neural reuse* (M. L. Anderson, 2014) and ecological theories (Newen, 2018a). ***The inferential mode of thinking does not seem to elude from framing the locus of the very way we think and interact with the world***. * For several centuries, distinctions were conveyed by visual and other sensory inputs. The very same objects of study such as the eye and the brain were then the medium of their own evaluation without a model of thinking being able to reach a level of better abstraction from analogies for this information. Archaeological findings during European Enlightenment progressively built on the evidence that prehistoric societies already considered the head as the source of many kinds of physical and mental symptoms (Walker, 1967; Majno, 1975; Verano, 2013; Broca, 1877; Horne, 1894). These common traits seem to have evolved towards early medicine fused with mythologies and metaphysics during the development of many civilisations. By crossing descriptions found in surgical papyrus (eg. *Edwyn Smith Papyrus*[6] and *Ebers Papyrus*[7]) found on Thebian sites in the 1860's, early Egyptian physicians seemed to be aware that symptoms of an injury could occur far from its locus while looking at head injuries (Breasted, 1930). This seems related with the way their medicine elaborated communication channels between different regions of the body. For Egyptians, the heart was the seat of the soul and organizing 36 channels towards itself. These methods and descriptions were known to be later transmitted to Greeks through the written *Histories* of Herodotus (Swayne and Havell, 2016) and the teachings of Alexandria and Memphis. Similarly to the Egyptians scriptures and their transmissions, one can find parallel vessels for these ideas in the *Hammurabi's Code*[8] of Mesopotamia, the *Atharvaveda*[9] of India or the later *Charaka Samhita*[10], the later containing early traces of systemic surgical methods for dissections (Thorwald, 1963), which would be found vital in later experiments and intellectual disputes in Greek antiquity. The *HuangDi NeiJing*[11] of China could also be regrouped in a similar fashion and contained writings and strong beliefs on the connections of the eye with the brain. In parallel to the constitution of universal elements in Pre-Socratic Greek thinking (eg. Pythagoras, Empedocles), began the earliest recorded dissections in Crotona by Alcmaeon. He described the optic nerve and its connection to the brain (McHenry, 1969) which led him to propose the brain as the central organ of sensation and thought.

Similarly, Anaxagoras, founder of the Athenian school, proposed to observe the brain as the organ of mind. Hippocrates and his medical treatise, the *Corpus Hippocraticum*[12], described the brain as central in the functioning of the body (eg. *On the Sacred Disease*) and rejected religious relations to bodily symptoms although the physical elements in quaternary theory based upon Pythagoras and Empedocles foundations pervaded into the grouping of body fluids and flows (Mettler, 1947). During the birth of *Anatomy* in Alexandria, and throughout the numerous transcribed dissections of Herophilus, the brain began to be more and more divided into regions of investigations, and challenging logics. While being progressively associated with the *psyche*, the first clear dissociations into parts occured mainly to distinguish obvious and apparant physiological differences (e.g. the nerves, the tendons, the cerebrum, the cerebellum). Despite

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[6] See "Edwin Smith Papyrus." In *Wikipedia*, October 13, 2019. link.

[7] See "Ebers Papyrus." In *Wikipedia*, November 25, 2019. link.

[8] See "Code of Hammurabi." In *Wikipedia*, December 2, 2019. link.

[9] See "Atharvaveda." In *Wikipedia*, November 19, 2019. link.

[10] See "*Charaka Samhita*." In *Wikipedia*, November 30, 2019. link.

[11] See "*Huangdi Neijing*." In *Wikipedia*, August 14, 2019. link.

[12] See "Hippocratic Corpus." In *Wikipedia*, December 2, 2019. link.

the progressive foundation of a rationale for greek medicine, scientific proofs and arguments remained deeply linked with philosophical analogies and led the rethorics for debating on the seat of the soul. Two main opponents can serve as flag bearers of the dispute. On one hand, Democritus and Plato who represented a major shift to the inherited idea of a cardiocentric theory (Plato, 300BC), believed in a threefold soul. In the head would be found the intellect, in the heart would be anger, pride, fear and courage, in the liver or the gut would be lust, greed, desire and lower passions (Mettler, 1947; J. Wright, 1925). On the other hand, Aristotle, influenced by other cultures, indulged the heart as the *acropolis* of the body, in accordance to Mesopotamian, Egyptian, Jewish, Hindu, Chinese, and earlier Greek traditions. For him, as the heart was related to warmth and the element of fire, it was also the seat of intellectual, perceptual and related functions for the soul. The arguments of the dispute heart/brain over the placement of the soul and their roles remained unresolved for many centuries and are still subject for questionable supremacy in the evolving sophistication of modeling intelligence and its enabling material. As for example, in the contemporary studies of the enteric nervous system (Furness *et al.*, 2014; Annahazi and Schemann, 2020).

Figure 4: Painting of *The Agnew Clinic*, Thomas Eakins, 1889. John Morgan Building, University of Pennsylvania, Philadelphia. Source: link

By the end of the 19th c., studies on the nervous system would have formed an investigation more focused on the brain while keeping a dialectic order between functional localisations and holistic approaches. Following the influence of Celsus[13] and later Galen[14] in the 2nd c. of the Roman Empire, important notions such as *sympathy* for the autonomic nervous system and *rete mirabile* for the brain established a strong basis for an account of the intellect generally located in the brain but without definite segmentations (Rocca, 2003; E. S. Smith, 1971). A more discrete ventricular and theological localisation became a leading replacement from the 4th c. and perdured even during Renaissance to explain neurological signs (Nemesius, 2008; Guainerio, 1481; Benton and Joynt, 1960). The growing adoption of anatomic depictions by that time, throughout the works of Paracelsus or Vesalius (Guthrie, 1940), eventually led to requestioning the capacity for intelligence in the physical material of the brain due to disproved accuracy and

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[13] See "*De Medicina*." In *Wikipedia*, November 18, 2019. link.

[14] "Galenic Corpus." In *Wikipedia*, November 4, 2019. link.

beliefs of previous methods (Rosner, 1974; Singer, 1952; Spillane, 1981). But a general increase in resolutions of observations occured during the period of the *post-renaissance Man* in the 17th c., as in the works of Thomas Willis (Willis, 1664) where comparative anatomy is taking a turn towards materialist functionalisations focusing on brain functions[15]. Followingly, the 18th c. saw the emergence of animal electricity as an idea of flow of information throughout nerves of some kind (Brown-Séquard, 1860; Keele, 1957) and early cortical localisation of differentiated functions became purports of human understanding, thinking, judging and willing (W. Gibson, 1967; Schwedenberg, 1960; Ramström, 1910; Norrsell, 2007).The relay was passed on to Franz Joseph Gall in the 19th c. with the establishment of a *phrenology* (Barker, 1897) and where physiological features are associated as functions with underlying structures. The anglosaxon supporter of Gall's ideas, George Combe, widely transmitted these ideas through the *Constitution of Man* (Combe, 1923) and which became a most read competitor to the Bible in english homes (Young, 1968). By that time, it was such a pervasive idea that probing for such an elusive phenomena should find place into the tangible material of the body that it transpired even onto its physical/architectural apparatus and its pictural depictions such as in american scientific realism (see Figure 4).

In parallel to phrenology, the progress made in recording electric currents in brain activity with Richard Caton (Caton, 1875), cortical excitability with Roberts Bartholow (Bartholow, 1874), and cytoarchitectonic studies with Korbinian Brodmann (Brodmann, 1909) together led to an important corpus of ideas called the *neuron doctrine* (Finger, 2001) and identifying neurons as independent units and not entities fused with each other (G. M. Shepherd, 1991; Loos, 1967). From the early account of cerebellar cells (Purkyne, 1839), to Camillo Golgi and August Forel concurrent findings in the transmission of a stimulus without direct continuity but contiguity of neurons (Golgi and Royal College of Physicians of Edinburgh, 1886; Forel, 1887), and the subsequent work of Santiago Ramòn y Cajal (Cajal, 1888) defining neurons as autonomous units of the nervous system separated with gaps capable of communication (Foster and Sherrington, 1897), an emerging perspective on brain function being rather distributed than functionally located favored a more holistic approach which pervaded throughout the 19th and 20th c. (Finger, 2001).Equating the localization of symptoms with the localization of functions in neurology already drew a certain depth in the debate at that time (Hughlings Jackson, 1882; Prince, 1910). Friedrich Goltz was then stating what has become a standard view in neuroscience: the intellect cannot be localized in discrete cortical areas but there should be a necessary cooperation between parts in the sensory and motor system (Tyler and Malessa, 2000). Jacques Loeb was advocating for diffuse functions in the whole cortex (Loeb and Cattell, 1902). With a strong influence from the Gestalt of Wilhelm Wundt (Boring, 1950), holistic perspectives founded by Christian von Ehrenfels (Ehrenfels, 1890) emphasized the dynamically changing relations between identified parts of the brain. And subsequent theories such as the diaschisis of Constantin Monakov (Carrera and Tononi, 2014) fell into similar tracks to explain distal effects of brain lesions. In a relatively short period of time compared to previous shifts of ideas, more synthetic approaches emerged. Henry Head understood the cortex as a mosaic composed of foci of integration (Finger, 2001; Head, 1918). And Karl Lashley described higher-level integrations as a function of the dynamic organisation of the entire cerebral system while accepting specialized areas of motor and sensory functions in the cortex (Lashley, 1929).

Both approaches represent the current synthetic thesis of contemporary brain theories. And one cannot help but see the legacy of the debate imprinted in both the development of the philosophical debate in a *Theory of Mind* (ToM) and its operational pendant that followed a

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[15] Illustrations were made by the architect Christopher Wren. It is still unclear to which extent this collaboration influenced Wren's work. On Willis' side, this work greatly enriched the vocabulary with precision and among which the term 'neurology' was established. See for example: (Neher, 2009)

divide in representing its mechanisms. . It is always, by design, speculative to describe the evolution of ideas throughout history. But one can argue that the journey of seating the soul and intelligence throughout the body and the world is actively simultaneous to the one of observing and grasping these very two objects. Balancing between emulating certain beliefs, and attempts to stabilize certain truths. The lesson here might be that ***particular events existing in appropriate domains (ie. Time and Frequency) may not have necessarily a stable projection in another domain of localisation (ie. space)***. The recurrent issue in the history of ideas in neuroscience, that a phenomena that is observed must account for an underlying structure, led in great proportions to ideas that similarly observable analogies may be applied to the mechanisation of symbol processings. *

1.4.5 *Minds Without Meaning*

What has been considered as the foundations of experimental psychology, from the end of the 19th c., throughout the works of James Cattell and Wilhelm Wundt at the *Leipzig Laboratory* inititated in 1879 (Cattell, 1928; W. Wundt, 1910; Eisler, 1902) along with its drastic evolutions, from the second half of the 20th c., had formed by then a massive front against the predominent views of behaviorism (De Almeida, 2011). In a seminal paper of that particular period, Noam Chomsky adressed the commonly felt issues that the current models founded by John Watson (Watson, 1924) and developed further by Burrhus Frederic Skinner (Skinner, 1938) could not entail the sophisticity of the mechanisms involved in language and the formation of meaning by only correlating stimuli and responses (Chomsky, 1959).

In the midst of that change, which necessarily involved the philosophy of mind and more vastly transformed cognitive science (Miller, 2003; Locatelli and Wilson, 2017a), two main positions progressively built new approaches to consider perceptual experiences and representational content. On one side, a general extension of Gottlieb Frege's integrated account of the mind (Frege, 1956) and which posited a centrality of the concept of representation (Burge, 2005, 2010). This *Representationalism*, also in continuity with John Locke's ideas (Locke, 1689b), assumes that the world is not directly perceived but mediated through mental representations. A fundamental aspect of computational theories of the mind such as in Jerry Fodor's (Fodor, 1975) and David Marr's (Marr, Poggio, and Ullman, 1982a). On another side, a form of *Relationalism* intended to explain conscious perceptual experiences as not reducible, or explicable, solely in terms of representational content but in relation to the world (Locatelli and Wilson, 2017a). In the relational perspective, the phenomenal character of a direct, or *veridical*, perception is then put forward as fundamentally non-representational because of its psychological relation to external and mind-independent objects (T. Nagel, 1974). Following, at varied degrees, the legacies of Bertrand Russell's *acquaintance* to objects (Russell, 1910) such as in Roderick Chisholm's *self-presentation* (Chisholm, 1977), Franz Brentano's *intentionalism* (Brentano, 1874) such as in Michael Huemer's reading (Huemer, 2001), or the *embodied* mind of Francisco Varela (Varela, Thompson, and Rosch, 1992), relational views brought their focus rather on the explanatory role of perceptual representations in regards to cognition and became mainly constituted by three kind of overlapping considerations. A form of *Naive Realism* which claims such irreducible relation with objects in the world —and which is metaphysically constitutive of both experience and its phenomenal character (Martin, 1997)—, relational views about the conscious attention to objects through *references* (Campbell, 2002) and direct object views claiming that perceptual representations such as retinal images do not participate to perceptual awareness (Brewer, 2007).

In both accounts, representational and relational, a common agreement appears on the causal relation between the mind and perceived objects. The dispute then spans across scopes from internal centrality which are mind-dependent, to environmental ones (Newen, 2018b). But wether or not the scope of causality considered in the philosophy of mind may affect the course of cognitive science should not directly affect the ground context made constitutive of this research. For what matters is to reappraise important aspects of this period which consequentially increased the importance of a *linguistic,* and more generally, representational *turn* (Rorty, 1967, 1979; Hacking, 1975) over a vast domain of knowledge including architecture (Jencks, 1977; Goodman, 1985a; Donougho, 1987), and to consider that the level of abstraction in a *Computational/Representational Theory of Mind* (C/RTM) may now be seen as ***a powerful and functional model for the articulation of meaning which operates at a symbolic/algorithmic level and beyond the traditionally shallow morpho-structural analogy*** (Alexander *et al.*, 1977; * Hillier and Hanson, 1984). For in the opposite and relational case, one would have to acknowledge that experiences possess content of external nature to the mind (Burge, 1979; Clark and

Chalmers, 1998; McDowell, 1994), and that there are obvious mechanisms to emulate them (Menary, 2006).

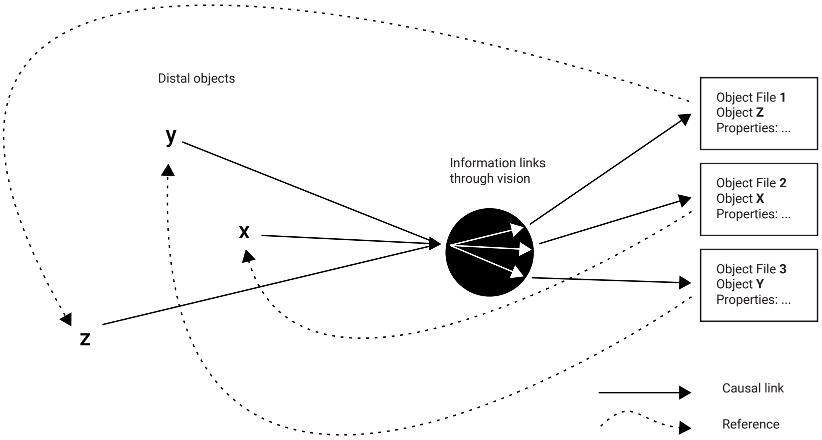

Figure 5: Diagram of the *Fingers of Instantiations* model, or *FINST*. The term was made in direct reference to a pointing finger as analoguous to pointing for demonstratives. Developped by Zenon Pylyshyn for a visual indexing theory of early vision and in collaboration with Jerry Fodor. Source: in Fodor , Jerry A., Pylyshyn, Zenon W., *Minds Without Meanings*, Cambridge, MIT Press, 2015, p95.

At which point, and which level of analogy an intervention may become technologically operational therefore becomes the vector that leads to models which would allow for modular and functional considerations. So it may become more fruitful to consider, in a functional perspective, that mental content supervenes phenomenal ones (J. Fodor, 1981; Williamson, 2000; Farkas, 2003). The way computational models on how the mind comes to produce meaningful expressions might provide the kind of basic analogies useful for architectonics and its articulating purposes. If there is a way to model how meaning could be referred to in the mind, it should consequentially apply, with parsinomy, to the mechanics of architectural articulations from a most basic perspective. To that end, the point of reflexion would not be to draw out from debates about imaging mental representations (Berkeley, 1709), or wether or not conceptual content holds meaning for mental representations (Gottlob Frege, 1891; Fodor, 1998). Despite their importance, it is ***the discursivity of mental representations and*** * ***its analogical reappraisal*** in such functional models as in C/RTM which may support such ground.For such an influential computationalist as Jerry Fodor who has drastically reshaped the general debate of cognitive science, some of the work of David Hume can be seen as an effort to build a naturalistic representational theory of the mind. A model of psychology using causal properties of mental states, or ideas, as basic materials (Fodor, 2003). And while the kind of representations used by that time were still at a prototypical stage (ie. ideas being considered as analogous to pictures), his associabilistic thinking became a fertile ground for further development in the formation of computationalist theories. Mental processes evolved from being considered as associations, to causal interactions. And the *humean* associative picture (Hume, 1738a) found a sounding replacement in the presence of the *Turing Tape Machine* (Turing, 1936) symbolised as a computational picture. Such computational imaging then became the basis of a theory of *Language of Thought* (LoT) (Fodor, 1975; Fodor, 2008). And while the tape machine historically constitutes a main pilar of connectionism, it also became a foundation of its symbolic antithesis throughout two main arguments. — The *productivity* and systematicity of thought, in its infinite capacity to generate meaning through *compositionality* (ie. the meaning of an expression is obtained from its constituents and their arrangements), in opposition to holistic perspectives (Fodor and Lepore, 1992). To that end, perception may only represent the beginning of beliefs fixations (Fodor, 1983) and allow the matching of a thing in the world to an idea in the mind (see Figure 5). — And the *modularity* of the mind, in direct relation to the idea of compositionality, where not only perception may be seen as an autonomous module from thought to the point of being penetrated by attentional weights (Fodor and Pylyshyn, 2015; Z. W. Pylyshyn, 2006), but concepts are seen through an atomistic perspective where ***Thought becomes prior to Language*** (Fodor, 1998; Fodor, 2008) and therefore cannot account for * pre-specific semantic structures. In that sense, it becomes possible to decouple the functional aspect of C/RTM from two ontologically irrelevant questions : the question of *consciousness* since computationalism cannot account for that matter (Searle, 1980, 1990), and the question of *meaning* itself since no meaning can be accounted for in mental representations of the mind (Fodor and Pylyshyn, 2015). The functional model in ToM then deprived of these two aspects provides capacious analogies through the trilogy of productivity, modularity and discursivity and which gateway for a research solely interested in emulating such capacity.

1.4.6 *Pendulums Without Gravity*

By lack of common agreement between symbolic and connectionist analogies to the modeling of intelligence, their joint history ressembles the trajectory of a pendulum, which axis seemed to periodically de-revolve to one or another position (see Figure 6). As if what was developed during one period or the other would not produce enough weight, tract enough gravity, but needed the input of its antithesis. Throughout the 20th c. and the present one, the now-scientifically ackowledged research field focused on the modeling of intelligence, and coined as *Artificial Intelligence* (AI), drew a fruitful dualism in approaches on how to grasp, and operate with, represented cognitive capacities. The term AI is, by now, known to have been coined during the foundational *Dartmouth Summer Research Project on Artificial Intelligence* in 1956 (McCorduck, 2004; Crevier, 1993; Russell and Norvig, 2003; National Research Council (U.S.). Committee on Innovations in Computing and Communications: Lessons from History, 1999). By then, what was loosely gathering varied conceptual orientations under the term of *thinking machines*, became recentered around AI, as proposed by the computer and cognitive scientist John McCarthy (McCarthy, 1996) as an attempt to take distances from the cyberneticist influence of Norbert Wiener. Even though constituted of many different subfields with their own specific filiations on how knowledge is represented, encoded and processed (e.g. *Neural Networks*, *Natural Language Processing*, *Vision*, ...), the two opposing paradigms of *Symbolism* and *Connectionism* encompassed the vast majority of them within AI. The binarisation of the debate stems from Cognitive Science (CS) at large, where the understanding of human cognition was divided between either symbolic or distributed natures (Forbus, Liang, and Rabkina, 2017). But as David Marr eloquently demonstrated in his seminal book: Vision (Marr, Poggio, and Ullman, 1982a), in order to account for effective theoretical models, different levels of abstraction, even dialectically opposed, need to be combined and without necessary dependency. His three levels theory of the cerebellar cortex (computational, representational and implementative) being the demonstration. Also foundational to the birth and nurturing of AI, were the *MACY* conferences. Spanning between 1941 and 1960[16], they gathered scientific research not only around cybernetics, but also neuropharmacology, group processes and the neurophysiology of human behavior (Heims and Heims, 1993; Pias, 2016).

From the long-standing tradition of formal reasoning, human thinking, as the manipulation of symbols, was sought to be mechanised in a coordinated but conflicted fashion among the scientific figures and institutions involved. While the proclaimed distanciation with early cybernetic/connectionist models was a clear manifestation of a symbolist standpoint, the timely birth of both AI and CS shaped the efforts towards the computational modeling of reasoning (Gardner, 1985). But shortly after the beginning of the MACY meetings, the first mathematical model of a single neuron appeared as a network analogy of neural events and activity (McCulloch and Pitts, 1943) and quickly became the starting point of connectionist models. While originally designed as an experimental instrument in neurophysiology, it found itself associated with the *learning behaviors* of the neuropsychologist Donald Olding Hebb (Dupuy, 2005) who coined the term *connectionism* (Hebb, 1949). The amplified contribution of Frank Rosenblatt by adding learning mechanisms to this model (Rosenblatt, 1958) ended to create sufficient momentum for the first major connectionist period to blossom. From the logical programs developped in the 50's by Herbert Simon and Alan Newell (Newell and Simon, 1956), to the formal critique of the perceptron by Marvin Minsky and Seymour Papert (Minsky and Papert, 1969), the pendulum then changed its axis to revolve around symbolic developments. It followed a series of numerous and significant events which generally served in favor of one or the other side; among which: the evolution of symbolic AI as *knowledge-based*

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[16] including the preceding but formative events to the *MACY* conferences on cybernetics: *The Cerebral Inhibition* meetings circa. 1941-42, and the *Group Processes Conferences* until the end of 1960.

systems, the diffusion of categorical logical rules in probabilistic inferences, the progressive loss of categorical data from the world due to its increasingly vast amount and its subsequent digitization into atomic standards (eg. shapes to pixels, phonemes to frequencies, words to letters, . . .), the evolution of connectionist AI into *parallel distributed processing* and its reappraisal of biological neural communication flows, or learning mechanisms for non-linear functions such as *backpropagation* (Cardon, Cointet, and Mazières, 2018).

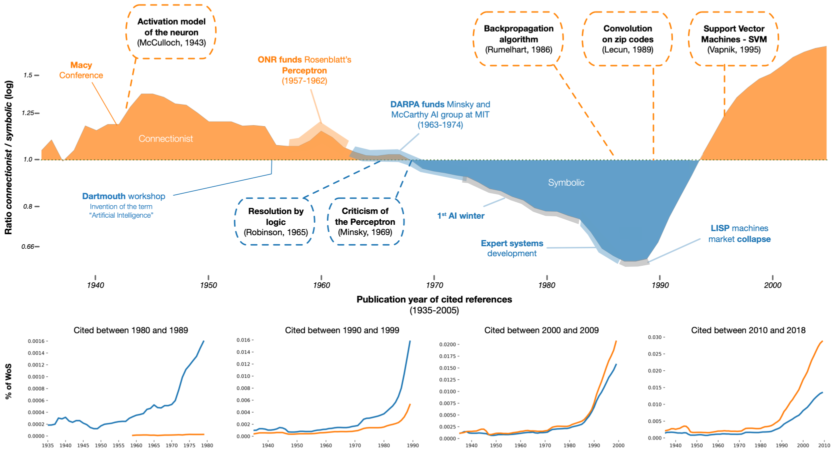

Figure 6: Evolution of the academic influence of connectionist and symbolic approaches to AI. Source: Cardon, Dominique, Jean-Philippe Cointet, and Antoine Mazières. *Neurons Spike Back. The Invention of Inductive Machines and the Artificial Intelligence Controversy*, translated by Elizabeth Libbrecht. Réseaux 211, no. 5 (2018): 173–220.

But what was then an active ideological debate spanning over the second half of the 20th c., began to slowly fade and lose gravity in our current century. The obvious observation came that, as such models advance in generalisation, sophistication and critical reviewings, successful connectionist models must include symbolic components —such as the *Monte Carlo Tree Search* of *AlphaGo* (Fu, 2016)— and powerful symbolic models must have mathematical mechanisms implemented in a computational neural network —such as *IBM's Watson* (Forbus, Liang, and Rabkina, 2017). One can easily understand, based on previous sections of this chapter, that the dialectic opposition was mainly based on analogies drawn out of legacies from mathematics, logics, and the foundations of neurology. An it should not come to surprise anymore that such a foundational work as the *Turing Tape Machine* in computation known to be a cornerstone of the connectionist approach, became also one for symbolists[17]. When it comes to built a computational model of reasoning with an intent, it would be hard to avoid ***the joint consideration of both atomic priors and distributed learning mechanisms***. To that * end, implementational, hybrid approaches started to emerge in order to account for symbol manipulations from neural networks (Marcus, 2001; Kahneman, 2011; Mao and Gan, 2019). Two main aspects therefore became obvious in the synthetic outcomes of AI in the current period: the pursuit of more generalised learning models seems to consider a level-based approach to fuse both paradigms in their respective temporalities of information processing, and purely distributed models looking to optimize complex tasks of high variance with unstructured data, greatly benefit from external human categorical inputs. In both cases, integrated or interactive, the distinction remains between the complementary capacities of the two paradigms as a virtuous cooperation. This would become an almost trivial comment on the history of ideas if it would not account for similar and fundamental concerns in architectural thinking nowadays.

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[17] see more particularly 1.4.5

As foreign from the computer and cognitive science debate as it might seem, architects remain in a perpetual search of symbolic articulations which are contemporary and operational. This must necessarily involve the notions of computation and its incidental distribution.

1.4.7 *Articulations Without Representations*

Another noticeable body of knowledge and contextually relevant to this research frames the kind of differentiation that happens between phenomenology, and its architectural pendant. If we were to consider the later as simply an offspring of the former and more general field of phenomenology, we would have to quickly disregard the intents and paradoxes developed throughout architectural endeavors. If one would be to consider architectural artefacts as simply part of the built environment, and the then built environment as simply purport of sensory information, considering ideas in architectural phenomenology instead of general phenomenology would be actually redundant and vacuous. As the later would subsume the former for its lack of specificity. But since one the fundaments of architecture lies in practical articulations, the understandings on where should lie such transformative act (eg. considering articulations in the perception of a phenomena, or its emulation) are of paramount importance.

It is to be noted that architectural phenomenology, throughout its development in the second half of the 20th c., sprung out of a form of criticism against technical modernism in order to develop discourses on a less mediated experience of the world. These efforts took a significant shape throughout personalities emanating primarily from the *Essex School* (Bedford, 2018) such as Dalibor Vesely (Vesely, 2004), Joseph Rykwert (Rykwert, 2000), and Alberto Perez-Gomez (Perez-Gomez, 1963). While functionalism and symbolization profoundly affected western architectural thinking, architectural phenomenology built upon prior philosophical efforts of the first half of the 20th c. to describe a non-representationalist perspective of experiencing the world (Husserl, 1936; Heidegger, 1927; Merleau-Ponty and Carman, 1945; Bachelard, 1957). Similar efforts could then be observed throughout a general and critical realism reflecting on architectural modernism, its fundamental nature and desire to maintain a rather *Classical* desire to represent *meaning*, *truth* and *continuity* in buildings (Steinmann, 1976; Eisenman, 1984). Paradoxically, such tradition and critical legacy from modernity could be traced further back in some other influent epochal ideas for the architectural understanding of experiencing space and its temporal agency. For instance, it has become common to understand how strong was the mark that Immanuel Kant left on philosophy at large from the 18th c. on, and incidentally on architecture as well. His developments on the limitations of reason by separating perception in the *phenomenal world*, from pre-structured percepts of the *noumenal* one (Kant, 1781a, 1790) left, by then, architecture to nurture in a superficial layer of the physical world, made of surfaces, and for which an exemplary embodiment can be found in the work and discourses of 19th c. architect Gottfried Semper (see Figure 7) as a form of *dressing* (Semper, 1860). Additionally in the following influent developments of physiological psychology (W. M. Wundt, 1874; Stumpf, 1873) and their direct assertions to architecture (Woelfflin, 1886; Vischer *et al.*, 1994; Göller, 1888), one can observe, a general critique reminiscent of a late baroque, an exhaustion in the production of forms. The overall idea that the production of architecture and its experience were operating on distinct temporal dimensions and could not be fully correlated was already layed out by then and entertained the seclusion of architectural thinking in its capacity to interact with the world. Followingly, a late *Gestalt* (Koffka, 1927) reinforced the understanding that cognitive
in the unconscious. The possibilities to consider the representation of any temporal agency for architecture were by then, theoretically severed and remained diffused in a paradoxical fashion into the idea that the built environment would bound the domain of capacity for architects (Rasmussen, 1964; Pallasmaa, 1986; Vesely, 2006), and even reassess the humanist analogy between human physiology and the built environment (Neutra, 1954; Eberhard, 2009). Where the only informative assertion would be mono-directed towards questioning how a physically present architectural artefact may affect human psycho-physiology.

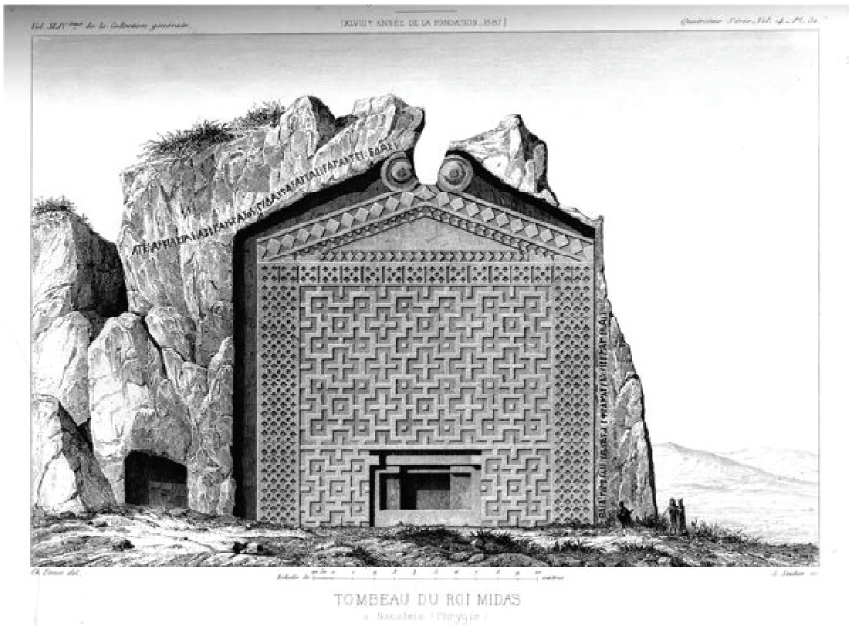

Figure 7: Drawing of *Midas Tumb* by Charles Texier and similarly used by Gottfried Semper in *Der Stil*, t.1, 1878 as a *paleontological* reference to the treatment reserved to architectural surfaces in his discourse of aesthetics. Source: *Tombeau du Roi Midas, Revue generale de l'architecture*, vol. XLIV, 1887, pl. 31, d'apres Charles Texier, *Description de l'Asie mineure* (1839), t. 1, pl. 56.

While a contemporary reading of architectural phenomenology could be brought forward as much more widespread and non-linear in references and interpretations (Otero-Pailos, 2010), the general comments previously drawn out remain. Architectural phenomenology directly starts from transposing its synthetic approach towards dealing with the world and its experience into tangible manifestations and its psycho-physiological phenomena as a natural distinction (Bedford *et al.*, 2018). Though, there is an universalizing desire to directly correlate the perception of a phenomena with its physical surroundings throughout a discourse of experience which paradoxically does not draw on representations. It is an ontological dilemma that architectural implementations of phenomenological discourses generaly put emphasis on the design of physical artefacts in order to enact a phenomenological experience. As it poses a clear temporal limitation on understanding and acting on the dynamics of experience themselves. There, again, lies a natural distinction on when architecture may start and end to converse with its perceptual and cognitive experience: from its physical embodiment to its sensory perception and cognitive articulation. But as called by Sanford Kwinter in its reading of modern theories sprouting from thermodynamics and the individuating features discovered in the intellectual efforts of moving through time and which largely impacted architectural thinking (Kwinter, 2003), an ontology of the event that deepens the potentials of virtuality is yet to be found. A linear reading of historical time and architectural design still remains. And this might very well be because, it is yet to be considered that architectural information does not reside onto its physical purports but is actively modulated by the human mind. Which consequentially means, if this remark is to be seriously considered as a potential for greater capacity, that ***architectural potentials also reside in the understanding and modeling of cognitive processes***. Since architecture does not entertain any measure to evaluate the phenomenal quality of its experience, its phenomenological relevance can only be assumed outside a potential rationalisation. That is, only if one considers phenomenology as a *linear* function of quality, as found in traditional phenomenology such as Christian Norberg-Schulz (Norberg-Schulz, 1981). But if one considers that the function at stake is unknown and more likely to be of *differential* nature, then it would be worth considering the flow of information between one phenomena (from the built environment) and another (from the psycho-physiological world of cognitive responses). It would not be surprising then to see that such consideration does not belong to architecture *per se* but rather cognitive science, information and communication in natural flows. In architecture, the fundamental problem lies in differentiating the phenomenological experience from its physical counterpart and what can be interpreted as a causal link. And causal mechanisms, at some point, must interact with intentional content. Which is what cognitive science is mainly about. Some causal mechanisms modeled in cognitive science might serve as great points of departure to emulate architectural articulations at a cognitive level. Paradoxically, the non-representational philosophical tradition has developed an interest in algebraic and symbolic representations found in computational models of perception (Dreyfus, 2002). ***If temporal agency and articulations do not have consistent spatial representations it does not mean that they could not have symbolic models as proxies in order to emulate these articulations instead of representing them***. *

A cognitive psychologist of note [. . .] commented recently, [. . .], that studies of the behavioral correlates of ERPs can be described as studies in which "phenomena are in search of a theory." [. . .] several years ago [...] another referee suggested that in the field of ERPs "one sees a technique futilely searching for phenomena!" We have, it would seem, made good progress in the last decade if we have found phenomena and are now searching for a theory.

- Donchin, Emanuel, 1979, Event-Related Brain Potentials, A Tool in the Study of Human Information Processing." In Evoked Brain Potentials and Behavior, 13–88. The Downstate Series of Research in Psychiatry and Psychology. Springer, Boston, MA. -

1.5.1 *Precedents in Architecture*

While theoretical and historical grounds have been unfolded above, particular points regarding corollary research positions shall now be raised.

Significant progress continues to be made in the multidisciplinary scientific research field of *Brain-Computer Interfaces* (BCI) since the 2nd half of the 20th c[18]. And as stated in a historic paper by Emanuel Donchin[19], the neural phenomena discovered by the end of this period still continue to draw theoretical debates on their causes, as well as cautious practical experiments on the modalities of technological instrumentation(Rugg and Coles, 2008; Bertolero and Bassett, 2020). If this alone can be seen as a healthy scientific context, it remains nonetheless an added layer of complexity on the role that related domains of cognitive science, and their development of subsequent technologies, may contribute in the advancement of architectural discourses and practices. An overall observation might be that the joint research of BCI and *Computer-Aided Design* (CAD) for architectural and design modeling at large still remain quite an underdevelopped field. Apart from episodic *half-realized* commercial attempts which failed to deliver their promises, and would not be worth mentionning any further, the research litterature seems to have placed the limit either to what extent particular objects may be recognized (Esfahani and Horváth, 2014; Rai and Deshpande, 2016), what particular cognitive ressources are involved in design processes (Gero and Milovanovic, 2020), or what preexisting *Human-Computer Interactions* (HCI) combination may be reduced to increase fluency of interactions (Huang and Chen, 2017). Which, arguably, does not seem to question, in respective order, the abstract level of modeling process of objects, the non-specific allocation of physiological phenomena to high-level cognitive processes which would rather be first modeled in language, and the purposedly high performance of interaction of such pre-exisitng interaction modes which remain unparalled.

On a more experimental and architectural aspect, research interests seem to have been marked either by multidimensional visualizations of neural activity and the development of related aesthetics (Novak, 2005; Roussel, 2016), or the spatial mapping of such activity in complex urban contexts (Collins and Hasegawa, 2010; Al-barrak, Kanjo, and Younis, 2017). While the former aspect may be justified as an evocative and stimulating means of creative acts in filiation with a most influential artistic work of Alvin Lucier (Straebel and Thoben, 2014), the later's relevance remains highly discussable given the kind of correlation being done between an observed phenomena and the high dimensionality of the environment being considered. On a more consistent perspective, the fused consideration of inference and affordance in response to elementary architectural dispositions may support the modeling of a probabilistic approach to the way such neural phenomena might correlate with particular spatial aspects of architecture (Djebbara, Fich, and Gramann, 2020, 2021). However, the temporal aspects of such inferential models remain solely at an interpretative level of perceptual events and do not aim for any active inference on architectural objects themselves. In brief, ***most research tracks remain focused on the after effects that architectural artefacts may have on, or more cautiously correlate with, human physiological responses and behaviours***. While the observation might seem harsh * at first, it nonetheless should not appear surprising given the informational complexity of architectural endeavors, whatever the sensory field (eg. visual, haptic, . . .) being regarded, and the fact that definitions of architectural or design modeling resist to be reduced as simply procedural schemes as well as architectural artefacts are not reduced to a built environment.

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[18] For key historical pointers, see the introductory paragraph of 3.1.

[19] See the inroductory quote above 1.5.

While an attempt to develop an adequate theoretical and technical framing of architectural modeling with neural potentials will be developped in the following chapters, a particularly significant historic marker should be evoked through the experimental work of Frederick Kiesler on *Co-Reality* and the educational project led at the *Laboratory for Design Correlation* of Columbia, New York, towards the end of the 30's (Phillips, 2010). Despite occuring in early technical developments of cognitive science, its architectural intent regarding the idea of modeling remains significant today in highlighting the untapped capacity of human cognitive vision into the design of inference loops between world objects and the human brain (see *Introduction* chapter figure 1), and where both ends remain active in the formation of new knowledge or its reinforcement[20]. Seen as a precursive work to this research, Frederick Kiesler's ideas on *Co-Realism* constitute a major reference in architectural ideas about modeling and which, instead of referring to through a lengthy analysis of his work aims at re-actualizing and extending. As we are advancing in the comprehension of morphogenesis for generative design and the evolutive integration of ambient data into that very generation, many transitions in the process between one step to the other are yet constrained under the necessity of human cognition and empiristic phases. The cognitive task of performing a selection of satisfactory generated results is yet to be performed as a separate and complementary process in the development of a morphogenetic design and leaving an important blur between a systemic design to satisfy a predefined set of rules and constraints, and the judgement/selection of a satisfactory performance. Similar observations can be formulated for any effort to automate Design-Build processes involving decision making and learning. A critical approach for architectural modeling in both its theoretical and technical layers remain to be investigated.

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[20] For an extended list of texts about F. Kiesler, see: link

1.5.2 *Authored Precedents*

While this current research started in 2016, it is worth mentioning some precedents which took place earlier in the form of episodic collaborations, workshops and papers. These precedents were later reconsidered as a research proposal upon the given opportunity of this PhD fellowship. Despite their embryonic stage, they contained important ideas which paved the way for a deeper understanding and further research.

During the course of the year 2012, a collaboration with neuroscientist Dr. Fabien Lotte (POTIOC, INRIA Bordeaux, France) was initiated as an introduction to the research field of *Brain-Computer Interfaces* (BCI). The general idea was then to assess for applicative potentials of integrating human cognition directly into computational models for C*omputer-Aided Architectural Design* (CAAD). This initiative was closely extended by exploratory workshops at the architectural teaching department *Digital Knowledge* of *ENSA Paris-Malaquais* (ENSAPM, France) and partly funded by a grant from the association of *Advances in Architectural Geometry* (AAG). This introductory work allowed to investigate typical methods for the data acquisition, processing and integration of peculiar neurosignals such as *Motor Imagery* (MI) and *Event-Related Potentials* (ERP) into simple design processes. In the scope of aiming for further experimental studies, a first prototypical generative design method, embedding neurosignals, was then proposed and named ***Augmented Iterations*** (Cutellic and Lotte, 2013). While still * in its infancy, the principle of this augmented iterative design process was to hypothesize on the possibility to create design objects of progressively higher visual complexity by the use of human visual discrimination among a rapid flow of generated design states. The principle was then also tested for the discrimination of states of shapes while focusing on the recognition of particular geometric objects in a constant flow of variations (Cutellic, 2014).

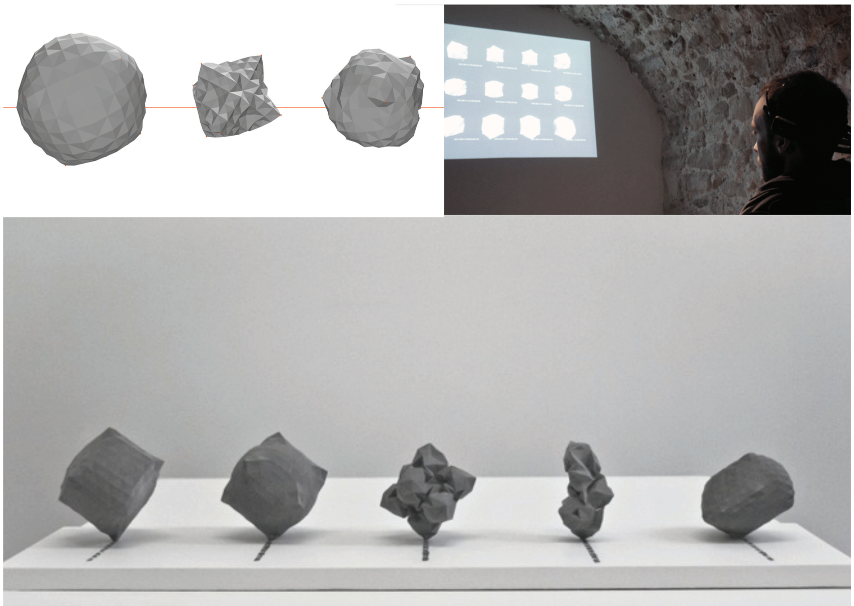

Figure 8: Pierre Cutellic, Le Cube d'Après, Non-Linear Neural Selection of Pseudo-Cubes, 2013. Initial experiments in shape discrimination. Described in Cutellic, Pierre. 2014. "Le Cube d'Après, Integrated Cognition for Iterative and Generative Designs." Proceedings of the 34th Annual Conference of the Association for Computer-Aided Design in Architecture ACADIA (ACADIA 14, Design Agency, Los Angeles) 473–78.

The outcome of these experiments led to the understanding that a richer territory of investigation was yet to approach, and that ***the combination of human and machine intelligence***
* ***for cognition and calculus*** could potentially lead to non-linear and non-convergent design
* solutions (see Figure 8). The hypothesis was that such a ***heuristic graft*** into computational design models would benefit from richer variance than typically rule-based generative models or other form of syntactical structures, where ultimately subjective choices have to be made and are only involved after completion of the generative process. These experiments opened a new ground for reactivating architectural research in the context of *Human-Computer Interaction* (HCI) and neural phenomena by applying evidences found in visual, ERP-based, and non-invasive BCI using Electro-Encephalography (EEG), to a generative design approach by *Rapid Serial Visual Presentation* (RSVP) tasks and combining both models of intelligence: *Human Intelligence* and *Machine Intelligence* in a closed loop.

However, deeper technical investigations and theoretical contextualizations remained to be sought for properly identifying both the means of exploring these potentials, formalizing adequate models of interaction, and understanding key notions of intelligence the way it is modeled scientifically and what is has to do with the idea of modeling in architectural design. A later written article initiated a theoretical and historical understanding that a part of the development of architectural discourses which had to deal with the emerging signs of the information age and artificial intelligence during the second half of the 20th c. in the city had to deal concurrently with a certain incapacity of understanding their protagonists. Architectural knowledge, in the face of evolving information and communication technologies would have to also evolve its understanding of human cognitive capacities and its interactions with technology in order to thrive (Cutellic, 2016). This new horizon became the one of the present research.

1.6 SUMMARY

From an understanding of being contemporary to the 21st c. as an architect, and positioning the research on technology for architectural modeling together with the modeling of intelligence, several points were gathered and for which a common contextual ground emerged towards the second half of the 20th c. until now. The computational project of this research briefly aforementioned, and developed in the following chapters, then gains its orientation and motivation from these very points raised to the role of ground contexts, as main intellectual vectors, symptomatic of the times, to act on.

Within the scope of formalising a general capacity to articulate sense as a modeling technology, the lessons from modernity and the influence of information and communication science onto architecture led to look for points of context ordered by the developments of computation. In an intent to clarify the personal position held within the current architectural debates involving computers at large, the hierarchical relation then put forward between *computation* and *digital* (ie. between encoding information and coding its reproduction) served as a departure to provide apophatic definitions of key aspects of the computational modeling of intelligence and its involvement for architecture; and where knowledge was to be sought among several points instead of a particular center.

The way the notion of reason was treated from its philosophical conceptualisation of the late enlightenment period to its scientific rationalisation following the developments of modern computation, led to a clear separation in two parts which were once fused together : *mindfulness* and *rationality*. Yet, throughout the objectivation of reason, and the standardisation of human decision making under an over-increasing concern for how to deal with uncertainty and the probabilistic dimensions of the world, the participation of human choice in the project of modeling intelligence resurfaced after the naturalistic ideologies of reason were casted away. Intelligence was remodeled without reason.

Following the tracks of modern rationality, a main train of thought leading the way to contemporary computation was the one of a universality thesis. Where all phenomena of the universe are supposed to be computable. The hypothesis of the universal computer was applied to almost every branch of scientific fields which had to deal with a computer and including the philosophy of mind. However, despite the desire to give a computer the property of universal graspability, certain boundaries persisting in being non-computable, and seminal mathematical works, might have proposed an alternative, and somewhat more potent, approach to consider the notion of non-computability as a placeholder for greater interactions. Where novel information and greater forms of abstract informational processing may operate and articulate *formalisation* with *signification*. In that sense, a greater capacity of computational power to operate in the world may lie in its incomplete character. Computation does not need universality but rather incompleteness.

Intimately linked with the debate about the mechanisation of the human mind, was the invention of neuroscience. And the scientific necessity to ground evidence into localised regions of the human body with an increasing resolution pertained until the very concept of information allowed for better abstraction and reasoning. The rational thought that particular phenomena must account for observable underlying structures then have obfuscated the understanding that *events* and *places* may not share similar domains of occurence. A notable reminder of ontological dilemmas produced by a materialist anchorage of abstract scientific modeling.

The philosophy of mind plays an important contextual role in articulating ideas about the modeling of intelligence and the generation of significance, or meaning. Despite the rather superficial diffusion of a linguistic turn in architectural thinking, a far more important representational turn allowed for thinking about the human mind as mediated from the world through mental representations of some sort and which do not necessarily entail linguistic structures as a prior. Where such representations may then provide for the articulation of meaning prior to language. In operational terms, representational content offers more potential than phenomenal ones by providing means of modeling how meaning can be referred to in the mind, and emulate the kind of capacity that the mind contains. Namely: productivity and systematicity in generating meaning infinitely. Precisely what a computer cannot do. *Meaning* and *representation* can followingly be decoupled from each other in computational theories of the mind. And representational/computational models may then be thought as mechanisms of emulation rather than supports of meaningful content.

No surprise then that within such theoretical and disciplinary debates around the modeling of intelligence in cognitive science, the formation of a scientific field dedicated to systemize and mechanize its models developed antagonist analogies. The symbolic birth of AI leaned towards a connectionist thesis to be first heavily disregarded before an increasingly powerful computational power supported its reinstatement at the end of the 20th c. and where it started to steadily blossom. However, as we stand now, with the overarching necessity to find meaningful patterns of information in multidimensional data of an ever-increasing volume, the joint consideration of symbolic and connectionist models to build machines capable of intent became a unified front of research to benefit from the wisdom and greater capacities of both: symbolic manipulations from distributed neural networks. The once polarized models of *atomic priors* and *distributed learning* mechanisms into a pendulum with great momentum tends now towards ensembles without gravity in order to look for symbolic articulations which are contemporary and operational.

Yet, a general understanding of a contextual body of knowledge that envisions architectural potentials in the technological modeling of intelligence would not be complete without the notable architectural discourses attempting to draw on causal mechanisms between the built environment and humans. The specific reading and position taken about architectural phenomenology, in the face of computational/representational models of intelligence, is of antithetic nature and intends to place the research in terms of *emulating* an experience rather than *articulating* it. For it is assumed that if an experience can hardly be measured, certain causal mechanisms may purport for cognitive articulations of meaningful representations. While architectural phenomenology has mainly inherited from a resentment against scientific representationalism, it may very well has obfuscated its ability to frame the capacity of architecture to act at a cognitive level and therefore remains, at the times, technologically irrelevant.

Incidentally, a major part of research involved in correlating psycho-physiological phenomena to the built environment stay focused on the reported effects that architectural artefacts may convey in such responses and behaviours. Several authored efforts, prior to the present research, have been synthetically described to scheme hypotheses on the technological combination of human and machine intelligence through the study and implementation of methods greatly developed in Brain-Computer Interfaces in order to propose more active and potent ways to design things in the world, as drawn from information and communication principles. The following chapters are, in large part indebted from this critical, contextual reading and precedent work.

Pierre Cutellic, *Le Cube d'Après, Non-Linear Neural Selection of Pseudo-Cubes*, 2013. Photo credits, Leslie Ware.

MODELING WITH NEURAL POTENTIALS 2

Next page: *Tintern Abbey in a bend of the Wye*, William Havell, the Ashmolean Museum, Oxford, 1804. Source: link

> *You think philosophy is difficult enough, but I can tell you it is nothing to the difficulty of being a good architect.*
>
> *- Wittgenstein, Ludwig, in Rhees, Rush (ed), Recollections of Wittgenstein, Oxford University Press, New York, 1984, p126. -*

Nothing is ever more complicated than explaining most common and general things such as *'space'*, *'world'* or *'model'*. It appears that these items of language which one uses casually to make sense of the world, to model a space of understanding, are subject to ambiguity, contingency, multiplicity. That is the non-exhaustive richness that one, at least, can agree with throughout ones contemporary lives. And by doing so, pervades in architecture and architectural intents to make sense of the world. There are however, potent ideas circulating around the very object of a model in scientific thinking which offer ways to frame such *ungraspable*. And there are also fundamentally basic elements of *architectonics* that correlate with that thinking in order to articulate it. Together, they should help to form a different path of understanding about computation that is operative and productive for architectural modeling. One that is conveying messages at great capacity in the face of information and communication technologies inherited from the past centuries and activated nowadays.

2.1.1 *Models and Modeling Them*

While models benefit from an extremely rich history and literature, wether scientific or non-scientific models, they belong in the history of ideas to the chapter of their formalizations. As an analog representation of this idea and its beliefs, offered for collective comprehension. This section will not deploy the whole debate on models, of importance spanning beyond concerns of this research, but simply to hold some points providing somewhat plausible and foundational answers to - what is a model - what is modeling - and what has architecture to do with it ?

As a most general introduction, one can start by discerning the object of a model in scientific and philosophical reasoning as establishing its relation to the natural world through boundaries. As a thought experiment, and as abstract as it might be, a model routinely claims and defines both a space for reasoning and the validation of it. It constitutes a world in itself with its own rules and language, which might not hold true outside of it but maintains coherence within. Being aware of such model nurturing an idea is dealing with what lies beyond its boundaries, its limitations, and enables better understanding of how to operate with. We shall see two dialectically opposed, though complementary, kinds of conceptual models in the way they deal with such endeavour: *demons* and *gnomons*. Demons occupied by objectifying boundaries and gnomons by transcending them. While we will synthetically mention etymological and historical studies of the two figures, we will focus on pointing out their main features for the modeling of ideas and their implementations.

As stated by Friedel Weinert (Weinert, 2016), demons are recurrent figures in the history of scientific and philosophical reasoning about the world. Used as argument patterns, they fulfill the function of probing for the coherence and limits of human knowledge about the natural world by setting limitations, metaphysical constraints, beyond current understanding through new hypotheses and somewhat counterfactual, as a virtual limit, to be reached out by thought experiments and allow for a new measure against current knowledge. To that end, they inform of what is missing in that understanding. Perhaps the most ancient depiction of using that thought process can be found in the traveller experiment of *Archytas of Tarentum* (see Figure 9) to elaborate a discourse against the limitations of the ancient Greek geocentric worldview (Weinert, 2016). And to summon a few other corollary ones along the vast history of ideas: *Laplace's demon* provided for an extension of Leibniz's idea on physical determinism and the constancy of information in nature (P.-S. Laplace, 1814), *Maxwell's demon* was adressing theoretical violations of the second law of thermodynamics regarding entropy (Maxwell, 1871), *Descartes' demon* opposed skepticism with doubt and opened scientific thinking of that time to a broadened space (Descartes, 1641), and Nietzche's demon borrowed from the Stoicists to define the idea of eternal recurrence (B. Williams, 1882).

While demons main feature consists in the setting of boundaries to probe for, gnomons represent another conceptual model mainly used to transcend them through projections. An already widely present model in Egypt and Mesopotamia (Isler, 1991; Savoie, 2018), which was passed on the Greeks (Swayne and Havell, 2016) to support the birth of geometrical thinking and convey the ancient legacy of abstraction of space (Serres, 1989, pp. 73–123). Even though gnomons were somewhat more tangible operations than demons by their original physical artifacts, they were commonly known as a cosmological method for geometric construction. their capacity for abstraction remained nonetheless fruitfull and could be reduced to a simple mechanism of projection from the stoicheion to tables or mnemotechnic devices in order to render information intelligible. Seen as an instrument of automatic knowledge production, the stoicheion was abstracted as a boundary to transcend and project onto another, more

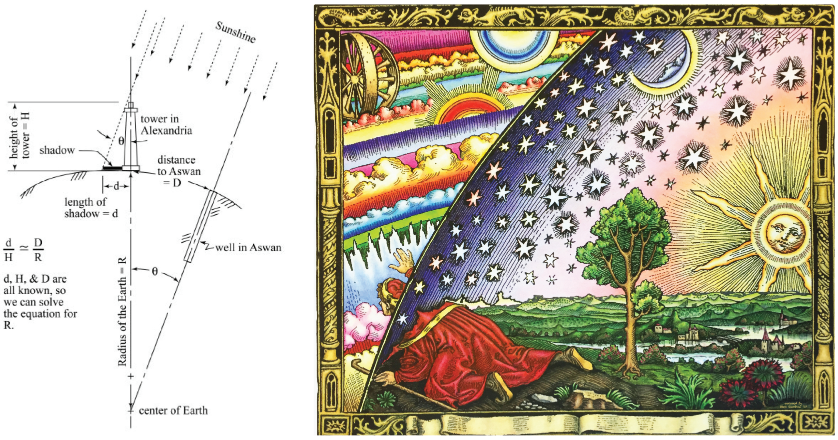

Figure 9: Depictions of two of the most ancient and important demon and gnomon models in the history of scientific thinking. Left - An actualized diagram of the gnomon used by Eratosthenes to calculate the circumference of the earth from shadows projected by the sun on the ground, c. 240 BCE, source: Lienhard, John. 2003. The Engines of Our Ingenuity: An Engineer Looks at Technology and Culture. Oxford, New York: Oxford University Press. Right - The thought experiment of Archytas through a traveller reaching out at the edge of the known universe to devise of a possible extension without known limits c. 4th c BCE.

intelligible domain, by a diagonal projection. The homothetic relation would then prove the communication of preserved information from one domain to another through the notion of *invariance*. A very powerful yet simple geometric operation which would later reappear in the full-fledged concept of information As an exemplary application of that time, the polymath Erathosthenes of Cyrene used such model of thinking to calculate the length of the earth's meridian when there was no other practical means to find it (see Figure 9). The homothetic geometric model then allowed for finding a ratio to convert the projected shadow of the tower of Alexandria into to the sought measure of its supporting surface (the Earth) profile.

These two particular approaches, as prototypical models of thinking may now be seen essentially as a dual approach to deal with boundaries and knowledge while trying to probe for questions. When knowledge is found to be insufficient and limited, a demon may help to set virtual boundaries in order to reflect and extend it where it is absent. Through such operation of assymetry, it becomes experimental, as it allows for novel hypotheses to exist. When known boundaries need to be overcome in order to seek for novel knowledge, a gnomon may help to virtually project such obstacle on new grounds and produce relative information. Through such operation of analogy, it becomes instrumental, as it allows the transfer of valuable knowledge across domains. We shall observe, at the basic level, the benificial complementarity of these two approaches throughout our research on architectural modeling. *

2.1.2 *Archai and Architectonics*

While it is not a pursued goal of this research to look for origins of a body of thinking which enables the agency of architecture to remain active in the digital, it might be worthy to look for primordial definitions, and anchors in what preceded it, gave it momentum and a spectrum for what it *ought* to be. To that end, it is no discovery that the most anteceding and articulate references for historians and theorists interested in these aspects are to be found in ancient Greek philosophy, and its related ancestral knowledge taken from ancient Egypt, which appears through Herodotus *Histories* during 4th c. BCE (Swayne and Havell, 2016). As pointed out by Lisa Landrum (Landrum, 2015), the characteristic aspect of Plato's seminal writings such as : *The Republic* (c. 375 BCE) (Plato, 2018), *Timaeus* (c. 360 BCE) (Plato, 2000), *Critias* (c. 360 BCE) (Plato, 2016), *Laws* (c. 350 BCE) (Plato, 2019), *The Symposium* (c. 385–370 BCE) (Plato, 2020a), *Phaedrus* (c. 370 BCE) (Plato, 2020b) and *Philebus* (c. 360–347 BCE) (Plato, 2012), is that while all were adressing foundational ideas of architectural theories from the Renaissance onwards (J. S. Hendrix, 2004), they did not form the initial vector for architectural thinking, which can be traced and re-assembled through extant litterature on the concepts of archē and architektōn.

Concepts for which, Plato's *Gorgias* (c. 380 BCE) (*Plato - Gorgias* 2016) and *Statesman* (c. 360 BCE) (*Statesman* 2016), as well as Aristotle's extensive work on *Politics* (c. 350 BCE) (Jowett, 1984), *Physics* (c. 350 BCE) (Hardie and Gaye, 1984), *Ethics* (c. 340 BCE) (Ross and Urmson, 1984; Stock, 1984; Solomon, 1984) and *Poetics* (c. 335 BCE) (Bywater, 1984) furnish with significant content regarding the *architectonic agent* which is the architektōn and its intentions, rather than defining physical and geometrical aspects of the architect, the city and the cosmos as in the former corpus. Ample developments about various types of archai can be found in *Metaphysics* (Cohen, 2016) and constitute the important notion of *beginnings* for the architektōn. Indivisible elements to be articulated wisely, and which one should call now *parts*. For which the architektōn, as a prototypical figure of the architect, is to cultivate their articulations for greater ends. Through these texts pervade the constitution of architectonics, and which is to be found as a transformative act beneficial for the city and its citizens. While the later mentionned corpus of work from Aristotle seems quite vast compared to Plato's, the phylum traced about Aristotle's developments on architectonics is culminating in the *Nichomachean Ethics* (Landrum, 2015; Ross and Urmson, 1984). Overall, the combination of these dialogues from Plato establishes the main scope of the architektōn to be concerned by the furnishing of cognition (gnōsin) and to cultivate both a syncritic art (technē) and synthetic science (epistēmē) in order to weave the complex fabric of the city (polis). Within such scope, a practical wisdom must be sought (phronēsis) and strongly defines the following basis of Aristotle's architectonic intelligence (dianoia) (Landrum, 2015).

Throughout the practice of phronēsis, an architektōn may seek to both enact wisdom and its preconditions. However, the syncritic and encompassing nature of its act leads to a specific definition of its orchestration and relations to boundaries, to what it actually emphasizes and surrounds. Significant details appear in the notion of *place* (topos) as a result of such act, and which does not provide for division and circonscription, but rather an inclusive circulation of the goods in the polis (Hardie and Gaye, 1984; Casey, 1998). This particular aspect holds an important modality of architectonics, and which does not rely on hierarchical values but rather orders of magnitude between strongly defined points that are the archai. It tends to set a horizon rather than a straight path among them. This is also a corollary trait to be found in the dramatic direction of the architectonics that belongs to rhetorics in Aristotle's *Poetics* (Landrum, 2015). Through the articulative act of the architektōn, archai become poles of magnitudes in order to provide orientation and circulation within the architectonic domain

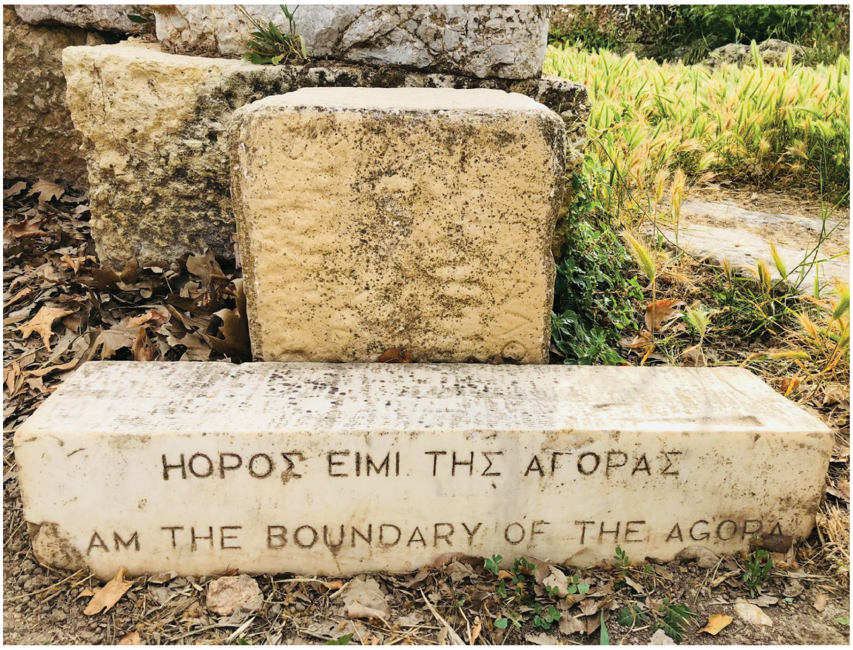

Figure 10: Agora Horos as territorial markers in Athens. While the stone is a re-enactment of the original artifact to accomodate for global tourism, each horos conveyed markings and symbols of particular value depending of their place of indication within the polis in order to provide for polarity without clear delineations and explicit notion of crossing. Image by Adrienne K.H. Rose.

that is the organization of the polis. The practical use of punctal stones (horoi) marking identities, places, general locations, and tresholds without property lines in the greek territory (see Figure 10) are a one of the few extant artifacts of such relation to boundaries through polarities establishing magnitudes and the negotiation of coexisting entities (Peterson, 1988; Pirenne-Delforge, 2018). However, the idea that such punctual markers might define a field of vision, a horizon, pervaded throughout history and can be also observed from later works on geometrical optics and perception through the *Horopter* of Aguilonius (Aguilón *et al.*, 1613; Ziggelaar, 2011) and later used by Desargues to devise on projective geometry (Desargues, 1639).

Such polarities, in the practice of the architektōn are to be the knowledge of first causes (archai), the starting points to articulate in order to bring a city's good into being with an appropriate mixture of particulars and universals. While the separation of architectonics from architecture allows for a clear discerning on the fundational aims of architectonics to balance and articulate miscellaneous elements of particular and universal claims, its most peculiar characteristic emerges from other forms of articulation. As it does not directly alter the nature of parts but re-establishes their values within a spectrum of magnitudes. They constitute a primordial reminder on the fundamentally dual process involved not only in the definitions of architecture, but more importantly in how ***architectonics defines at a basic level the act of modeling by identifying the archai which constitutes the syncritic world as polar boundaries, and articulating them by synthetic knowledge to emulate a spectrum of actions***. *

2.1.3 *Architectural Modeling and its Computation*

Since we have defined already the levels of abstraction in models of thought we intend to depart from, and the drastically minimal mechanism of architectonics we intend to emulate while developping methods for architectural modeling, we might as well ask now about the modalities of its encoding, its computation.

At the end of the 20th c., and with the formative arguments on the digital (Carpo, 2011, 2013), architectural modeling seemed to be deeply anchored in a discourse of continuity. The combination of french postructural aesthetics interpretating Wilhelm Gottfried Leibniz' differential calculus in philosophy (Deleuze, 1988a), and precursive computational ontologies of architecture (Cache, 1997; Beaucé and Cache, 2007), as well as american postdeconstructivists (Lynn, 1993, 1998) paved the way for a formal geometrisation of algorithmic thinking, which became intricately linked with the developments of the modern computer-aided approaches and computerized geometric modeling (Lynn, 2013; Bottazzi, 2018). This trajectory for continuity, and in a way also a tentative formalization of consistency in correlation with the one of mathematics and logics[1] from the end of the 19th c., became even so emphasized with the *non*-standard perspective (Cache, 1997; Migayrou, 2003) which marked, in reference to the differential modeling approach in the semiophysics of René Thom (Thom, 1990), a paradoxical inversion of continuity, as in the foundational geometry of Thales, between architectural objects and their encodings. The *invariance by variation* became the *variation by invariance* through the standardisation of digital codes of design and production. In a contemporary revision of *Elements* of architecture, Ludger Hovestadt polarizes *geometry as the rationalization of thought patterns amid known elements* constituting specific bodies of knowledge and capacities for modeling (Bühlmann, Hovestadt, and Moosavi, 2015b). *Euclidean* Geometry (Euclid, 300BC) being operative in the modeling of space, *Cartesian* Analytic Geometry (Descartes, 1637) in the one of time, and as for the digital, code being operative in the modeling of values. In that sense, one can approach geometry through its algebraisation, its abstraction operated by computation. Accordingly, we would not find particularly interesting to dwelve into the miscellaneous encodings of geometric modeling in computer graphics as we would now see them as free means of design expression, but rather tend to think that what computation has to offer for the modeling of architecture is an abstract reasoning of the topological order for the articulation of parts instead of their design.

Such level of abstraction in reasoning and what it may allow for would then need to refer to the constitution of a computational thinking rooted in operative algebra. The algebraic perspective on abstracting geometry through its computerisation is somewhat a legacy that took shape amid the birth of analytic geometry at the 16th c. with Rene Descartes (Descartes, 1637) and the axiomatisation of geometry by David Hilbert at the beginning of the 20th c. (Hilbert, 1903). An algebraic project, was born out of collective efforts to arithmetize mathematical intuition and took significant proportions towards the second half of the 19th c. with seminal works such as George Boole's algebraisation of logic (Boole, 1847, 1854b) or Richard Dedekind's denaturalisation of number structures (Dedekind, 1901). Concurrently, and inevitably related, these mathematical efforts revolving around the applications of algebra reflected significant impact on philosophical works of their contemporary period (Russell, 1897; Whitehead, 1898; Husserl, 1972), and for which remains a strong presence in nowadays reflections about computation and incidentally for our concern, architecture. A particular interest to that specific period, and more particularly exemplified by the work of Richard Dedekind, is serving as an ideal reminder of what would architecture have to do with computation nowadays.

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[1] see 1.4.3.

While his work has had modern reconsiderations about its mathematical significance and impact (Reck, 2008), here we join forces and reappraise ideas already developed by preceding works of Vera Bühlmann in synthesizing *Dedekind's legacy* for the search of engendering novel philosophical concepts (Bühlmann, 2012), and Nikola Marincic in drawing out information and communication models for CAAD from the same legacy (Marinčić, Hovestadt, and Bühlmann, 2019). The general and common point of interest lies here in the level of abstraction and structuration for the creation of numbers that leads to an objective way to deal with the idea of *novelty*. The so called *Dedekind cut* (see **??**), by then developed as a mean to produce completely new irrational numbers from two sets of rational numbers (ie. the cut between these two sets producing the irrational), exemplified the idea that numbers do not have to be considered as naturally given but rather as *free creations of the mind* (Dedekind, 1901). A form of objective reason, allowing for the computability of any newly created number. We cannot help but to think of a corollary intent in the search for productive endeavors, next to the idea of *differential modeling* by René Thom, and the *differentials of thought* by Gilles Deleuze[2] where the reinterpretation of Zeno's paradoxes[3] may serve as similar domain structurations to produce infinite amounts of new objects (Deleuze, 1969, 1968). There lies a common interest in providing an ideal for abstract structures which may allow for productivity, instead of representing specific structures which would consequently generate their own limitations (eg. syntactic structures). A form of *pre-specific* (Bühlmann, 2012) symbolic structuration which allow for an abundance of relations to experience, thought, language. The productivity argument, in the context of objective reason and pre-specific structures, is also a corollary to the previously mentioned work of Jerry Fodor in defining a *language of thought*[4]. All for which, computation provides a fertile ground. These observations, motivated by finding anchors to answer the question of what has architecture to do with computation, bring together the strongest and most potent feature of computation. ***Through its abstraction and structuration, computation may provide for operative and productive means of modeling***, while avoiding immediate limitations of representational structures. *

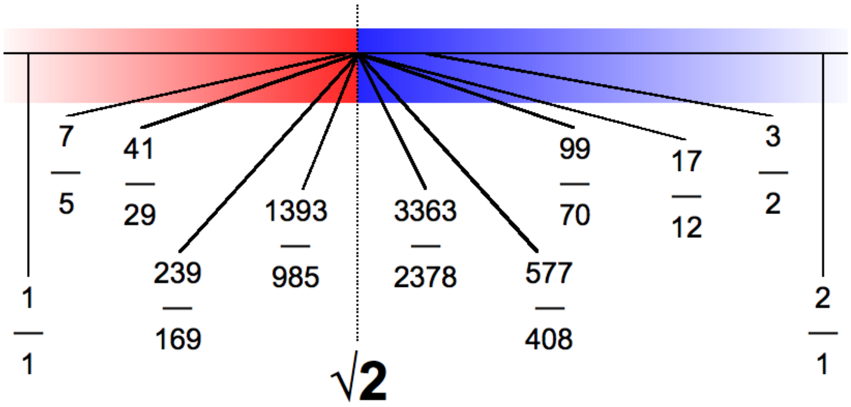

Figure 11: A Dedekind Cut is made of a partition of two sets of rational numbers (red and blue). The cut is an irrational number partitioning these two domains independently (square root of 2). Source: link

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[2] Vera Bühlmann also indicates this reference in: International Conference on Philosophy, Artificial Intelligence and Cognitive Science „Turing 2012" at the De La Salle University-Manila, Philippines, March 27 to 28 2012. Which equally appears as a vector of interest stemming from precedent research on her Phd Thesis : Inhabiting Media, Annäherungen an Topoi und Herkünfte medialer Architektonik, 2011. : link

[3] For a synthetic overview of Zeno's Philosophical Paradoxes, see: link.

[4] Jerry Fodor's thesis about human intelligence and its computational modeling is that there must be pre-specific structures in the mind which account for an infinite capacity to produce meaning, way prior to language and representational structures. See 1.4.5

2.1.4 *Codes and Messages*

It is very often difficult, while researching on architectural technologies, to not encouter a superposition of both the notions of *technology* and *technique*. For it is frequent to find claims of technical advancements under the label of novel technologies. This can only create confusions and denature the content of a technology and its capacity for which architectural means of expression is highly dependent. Inversing this relationship would reach close to alienation. In a dialectic formulation, technology is the modeling of mechanisms conveying an idea. It is the first transition from abstraction to concreteness in order to deal with the world. Techniques are secondary in that fashion. And implement these mechanisms concretely, by codifying them.

The issue arises when technique and technology become interchangeable terms in the articulation of ideas: the gears are thought to be the mechanism, and the code to be the message. Here, as in numerous other sections of the thesis, we follow a fundamental gesture which can be found in many scientific and philosophical approaches where a dialectization of the terms may offer a better overview of the level of abstraction each one may provide in regards to each other. The *computational* neuroscientist David Marr famously illustrated this distinction through the analogy of flying while devising of a *multi-level* framework of study for *vision* (Marr, Poggio, and Ullman, 1982b). Or, for the post-structuralist duo of philosophers Gilles Deleuze and Félix Guattari to anchor the principal function to practice a *discipline*, and activate particular *bodies of knowledge*, lies in the distinction of an *idea* being able to adress a *concept* (Deleuze and Guattari, 1991). This, in many ways, proposes to architecture a ***focus*** * ***on the messaging technology, rather than the subsequent coding techniques***. Though *coding* exhibits essential features of literacy for enabling architectural discourses on the computational (Bühlmann, Hovestadt, and Moosavi, 2015b) as well as their flourishings (Migayrou, 2018). But understanding that its overcherishment also represents a traditional intent to grasp higher levels of abstraction and potentiality through what was already noted in late 20th c. digital architecture as a *coating of innocence* (Beaucé and Cache, 2007), might support more appropriate positions. Similarly, was criticized the semantic legacy of logics in mathematics by Jean-Yves Girard (J.-Y. Girard, 2008) in the way it induces truth by algorithmic explicitation, as a form of revelation. This is reminiscent from the critical philosophy of the technē of Theodor Adorno and Max Horkheimer (Horkheimer and Adorno, 1944). As well as the extension of the logos defended by Jean-François Lyotard (Lyotard, 1988), or Fredric Jameson (Jameson, 1991) against universal codifications in postmodernist narratives. Although we are touching here subjects reticulating beyond particular practices, we can make the case by concentrating this perspective on domains of the late 20th c. in Information and Communication and consider, following Marshall McLuhan (Mcluhan and Lapham, 1964), that the understanding and modeling of communication mediums themselves as a form of infrastructure are of prior importance. This should allow to depart from traditional forms of architectural encoded depictions (eg. drawings, . . .) and tend to the very capacity of abstract mechanisms of modeling.

Just as noted by Michel Serres, the historic *revolutions* which dealt with the modeling and processing of information (eg. Greek Antiquity, Renaissance, . . .), even at a prototypical stage, are reaching a stage of civilizational importance[5]. Whereas the ones which dealt with their realization are mainly echoing with societal changes (eg. Modernity, Postmodernity, . . .). In the most exemplary period of early Cybernetics of the second half of the 20th c., and by what was described previously as a set of grounding contexts[6], one can consider the later. By then, a particular type of communication models appears to be based on encryption and coding (Wiener, 1948; Shannon and Weaver, 1949). This moment gathered and formalized two

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[5] Michel Serres, les revolutions culturelles et cognitives

[6] See chapter 1

important basic ideas which are key to notions of *learning* and *information* involving reflexions of circular causality and uncertainty. The idea of *negative feedback* in correcting modulations of information to maintain its flow, and the notion of *entropy* as a measure of uncertainty in communication signals (Wiener, 1948; McCulloch and Pitts, 1943). The point is not so much to reappraise the cybernetic period but to focus our lens on which particular vectors were trying to break out from it during the second half of the 20th c. and while doing so, were reminiscent of fundamental ideas about messaging information. These two main ideas can then be traced back further, respectively to Warren Sturgis Mc Culloch referring Descartes' *Treatise of Man* (Descartes, 1662), and Norbert Wiener referring Liebniz's *Calculus Ratiocinator* and the production of information by a difference engine (Leibniz, 1903). However, even noticed by its precursors, *the theory of control in engineering whether human or animal or mechanical, is a chapter in the theory of messages* (Wiener, 1950, pp. 42–43), and theories of learning and understanding through communication needed further development. In a second wave, another order of communication models arrived with Gordon Pask, and these notions took a notably idealistic turn with his *Conversation Theory* (Pask, 1976). Based upon the cybernetic legacy and natural communication models, a general theory of learning was schemed by conversations stabilizing knowledge (see Figure 12).

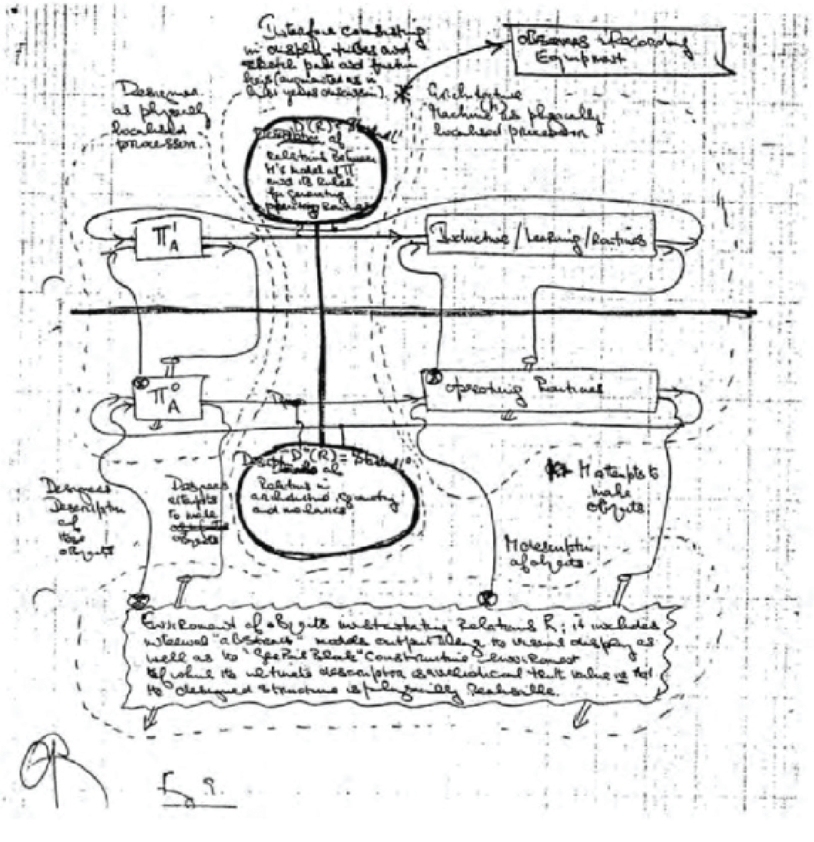

Figure 12: Gordon Pask's hand-drawn model of a conversation between a human designer and an architecture machine. Source: G. Pask, *Introduction to chapter 2 on machine intelligence*, in N. Negroponte (Ed.), *Soft Architecture Machines*, MIT Press, Cambridge, MA, 1976.

A prototypical language becomes here purport of information and a subject matter serves as a vector of explicitation, formalisation of analogies. Intelligence was there sourced by interactions and enabled by communication technologies. Gordon Pask was widely known and active in the architectural scene to bring a translational perspective on concepts of information and communication as well as how it could flow in meaningful realizations, but his ideas were always interpreted as a justification to yet again the directly projected realization of physical environments (Pask, 1969; Haque, 2007). Corollary to such effort, and contemporary to the period which had to deal with the influence of linguistic turn occulting the one of the far greater cognitive revolution[7], the literary critic George Steiner pleaded for the productivity aspect of transformational generative grammar (Steiner, 1975). Placing the codes as pure means of expression and from which meaning is externalized and brought to infinite capacity. The idea of an *expressionism* as originally defined by Wilhelm Worringer (Worringer, 1911) is of particular resonance in the fact that since codes are essential elements of communicating information, they also become objects of intuition. This is, eventually the most important aspect of coding which has purported the creation of values throughout the pictural period of abstract expressionism as well[8].

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[7] for a brief overview see 1.4.5.

[8] see the series of recorded courses of Gilles Deleuze on painting and abstract expressionism of the 20th century at: |href https://www.webdeleuze.com/cours/surlapeinturelink

2.1.5 *Modeling and Modulations*

If coding might be, from here on, understood as a form of expressionism, it would not suffice to simply purport information in order to make sense. A higher order of abstraction must then be achieved from a specific kind of transformation upon such codes. To that end, it would be useful to relate of the importance of this idea treated concurrently within the pictural domain of abstract expressionism which emerged similarly around the second half of the 20th c. For that matter, in art as in science, ***pictural modulations and algebraic convolutions are analogous to each other***. *

Further interesting points may be drawn out about modeling and more specially about the idea of modulations, where aesthetics and information find a common ground in the representation of gradual and continuous transformations. We shall begin by transposing the two terms modeling and modulation with the summoning of values and their transformations, while we will focus on the kind of continuity provided by this transformative act that is modulation. Through it, might become clearer the kind of relationship to pursue and correlate both in mathematics, painting and finally visual perception. At first, values ought to be organized along an axis of concentration which is bounded by two polarities of differentiation and confusion. This axis allows for attributing values in regards to specificities and commonalities. If we start immediately with an abstract generalization of what kind of transformation we are looking at, it is to both relate to the importance of algebra in that role and the fact that ideas we will later describe may be found through different forms but nevertheless are ramified to the same concept of modulation. As the brief argumentation unfolds, and even though we might refer later to a certain kind of pictural mode, we will see that the level of abstraction and generativity we are addressing here is not tied to a visual analogy. By the second half of the 18th c., the mathematician Leonhard Euler was already almost completey blind when he wrote about integral calculus and differential equations (Euler, 1768), and provided for the first mathematical integration of correlative operations between functions which will later be developed as a *Continuous Convolution Operation* along the two following centuries (Domínguez, 2015). Later found as more explicit formulations in the integral transformations of Joseph Fourier (Fourier, 1822), where functions may be composed of an infinite sum of harmonics, and Pierre-Simon Laplace (P. S. Laplace, 1812), where differential equations may be transformed into algebraic ones, the term *convolution* will find a stable ground only by the first half of the 20th c. by merging two influent graphic interpretations of the convolving and folding of functions, in the work on *analytic convolutions* of Aurel Friedrich Wintner (Wintner, 1935), and the term of *faltung* found in the work of Gustav Doestch on integro-differential equations, which also provided for the first stable notation $f(x) * g(x) = \int_1 f(\alpha)g(x-\alpha)d\alpha$. In current applications of *Artificial Neural Networks* (ANN), convolutions now allow for the temporal sliding of one function over another, and by doing so, the extraction of invariant spatial features which can then be represented as a third function of lower dimensions. Through the matrix multiplication of a data function and a sliding filter function, a feature map of lower dimensions may be obtained (see Figure 13). This transformation is generally held by the function of a kernel filter and, as is, might be seen as a *digital module*.

From what has already been described in the previous chapter, it would not appear strange here that the beginning of the 20th c. also marked the modern reflexion in art by a general rejection of illustration and narration to focus on abstraction and more direct sensorial communication approaches (Arnason, 1998). A conceptual perspective, and more sophisticated forms of abstraction were soon to come as an intellectual and aesthetic critic of what was then referred

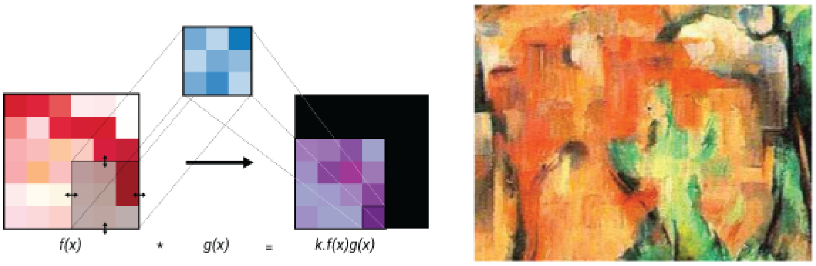

FIGURE 13: Right - A generalised depiction of a convolutional transformation in 2 dimensions. A similar representation can be extrapolated for n-dimensions. The kernel size and operations generally described in g(x) to transform the discrete values of f(x) into its convoluted result can vary depending on its purpose. It can be to reduce the size of the sample (as shown here) by pooling, or to reduce its dimensions. Original source: link. Left - A close-up of *The Sainte Victoire*, *Seen From the Quarry Called Bibemus*, P. Cezanne, oil on canvas, ca. 1897. Source: E. Loran, *Cézanne's composition: Analysis of his form with diagrams and photographs of his motifs*. Berkeley, Los Angeles: University of California Press, 1943.

as *retinal art* by Marcel Duchamp[9], as a mere pleasing of the eye and romantic definition of beauty pervading throughout most of the arts of the time. Through the development of *conceptual* and *abstract* arts, ideas conveyed by both trends started to overwhelm traditional means of standard communication when trying to express an intent or an experience that transcend former codes of representation. The idea of *figuration* as a mean of representation was progressively replaced by the idea of *presence* in order to convey meaning[10]. One could understand that as a modern tentative to intellectualize the optical domain and generalize its generative capacity in arts. Towards the second half of the 20th c., synthetic theoretical reflexions appeared to propose differences in capacity between languages, traditional codes, and the various emerging cultural and art forms of that time (Goodman, 1968; Sonesson, 1989). Similarly, for Gilles Deleuze, powerful ideas regarding information and communication became significantly present during that period[11] and took a significant turn with painters such as Francis Bacon (Deleuze, 1969, 1981). Most projects of abstraction in painting seemed to implement a pictural code, intrinsic to painting itself. While particularly visible in geometric abstractions early on in such work as the one of Vassily Kandinsky (Kandinsky, 1910) as an effort to draw meaning out in the world from the painting itself, a tension in communicating the content of a painting — being reduced to its code and losing its abstract capacity— became strongly present. This tension between conveying values through codes and maintaining such coding away from figuration is a general concern which pervaded the entire pictural movement dealing with the joined ideas of expression and abstraction (Deleuze, 1981). Analogically to digital values, the modulation of colors and light in painting was the transformative act which transported meaningful values at an abstract level through codes. Modulation became a regime for an aesthetic analogy of temporal and continuous variations across the canvas. This was * noted by Gilles Deleuze as a ***coding graft*** over the continuous flow of colors enabling an analogy to reach greater power[12].

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[9] see: Rosalind Constable, "New York's Avant–garde, and How It Got There", *New York Herald Tribune*, May 17, 1964, p. 10, cited in Jennifer Gough–Cooper and Jacques Caumont, "Ephemerides on and about Marcel Duchamp and Rrose Sélavy, 1887–1968," in Pontus Hulten, ed., *Marcel Duchamp*, Cambridge, MIT Press, 1993, entry for May 17, 1964. also: Duchamp as quoted in H. H. Arnason and Marla F. Prather, *History of Modern Art: Painting, Sculpture, Architecture, Photography* (Fourth Edition) (New York: Harry N. Abrams, Inc., 1998), 274

[10] See: The series of lectures of Gilles Deleuze on Painting, 1981: an english transcription can be found at link. The original is link

[11] See: Ibid

[12] See: Ibid.

While the idea of modulation seats in a long tradition of ideas circulating around the communication of abstract content from Pythagoras studies of harmonic relations (Crotch, 1861), to Leonardo Da Vinci's development of the *sfumato* technique to deal with the indeterminacy of light and colors throughout the canvas (A. Nagel, 1993), leading finally to one of the most emblematic painter of the modern period to conceptualize the idea of modulation: Paul Cézanne (Turner, 1998; Cézanne *et al.*, 2001). Through this work, the criticized idea of representation historically conveyed by modeling in painting found a conceptualization of the modulation of color as means to moderate chaos and indeterminacy in abstraction in order to express values intrinsic to painting. The hand-brush became an *analog module*. One can see from these two aspects of treating information in mathematics and arts that the convolving of numerical values in matrices has an equivalent in the modulating of chromatic values on the plane of the canvas (seeFigure 13). Convolution is the computational equivalent of modulation in painting and together they express the necessary transformative act which must accompany the use of abstract codes.

> *Remembering is not the re-excitation of innumerable fixed, lifeless and fragmentary traces. It is an imaginative reconstruction or construction, built out of the relation of our attitude towards a whole active mass of organised past reactions or experience [ie. Schema], and to a little outstanding detail which commonly appears in image or in language form.*
>
> *- Bartlett, Frederic, 1932, Remembering: A Study in Experimental and Social Psychology, University Press, Cambridge, p213. -*

It is generally understood that the most generic and all-encompassing term used to refer to the formation of knowledge and understanding through modalities of experiencing, sensing and thinking is *cognition*. Loosely, cognition gathers all modeled actions or processes enabling intelligence (Matlin, 2017). This includes the acquisition of information as in sensation and perception, the selection of information as in attention, the communication of information as in language and numbers, the representation of information and its understanding, the retaining of information as in memory, and its behavioral use as in reasoning and motor coordination. The vastness of what tentatively accounts for an understanding of intelligence also reflects its importance throughout the history of ideas. The modern period of the cognitive revolution[13] took roots through discrete periods of time such as in the works of Plato's *Republic* in binding the *polis* and the soul during the 4th c. BCE (Plato, 2018) and followingly Aristotle's *belief* in his notion of rationality (J. A. Smith, 2021), William of Ockham's *Intuitive Cognition* in the medieval period of 14th c. (Ockham, 1986), René Descartes' *Cogito* (Descartes, 1637) and John Locke's *Theory of Perception* (Locke, 1689a) of the 17th c. Enlightenment period, Hume's *account of the mind* in the subsequent 18th c. (Hume, 1738b), Frege's *cognitive significance* in his *theory of reference* (Frege, 1892) and Wilhelm Wundt's observation of experience through *introspection* (W. Wundt, 1907) at the end of the 19th c, Bertrand Russell's *acquaintances* in his theory of knowledge at the beginning of the 20th c. (Russell, 1910), or Wittgenstein account of memory and embodiment (Wittgenstein, 1980) among many other influential ideas which reticulate independently beyond cognition itself.

But amongst the development of understanding cognition and the way one can relate to things in the world, fundamental aspects about the modality of creating values were developed through a sophisticated understanding of memory as a way to form prior knowledge upon which discrimination of new sensory information can be made. With modern seminal works such as Frederic Bartlett's generative capacity of memory (Bartlett *et al.*, 1932) or Jean Piaget's developmental dynamics of memory in his theory of cognitive development (Piaget, Brown, and * Thampy, 1975), one began to envision ***memory as an active instrument of measure***. Throughout such extensive body of knowledge, one might ponder to which extent, on a philosophical and psychophysiological basis, such instrument may relate to things in the world and to which extent its dynamics may operate.

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[13] For a brief overview of the consequences of that period on the ideas developed in experimental psychology against behaviorism, and later to the philosophy of cognitive science, see 1.4.5.

2.2.1 *When Things Become Objects*

A question we should ask here prior to considering memory itself, is to ponder at which point, in the perceptual domain, a *thing-in-the-world* might enter the mind without collapsing into mental representations to become an *object-to-the-mind*.

In a most general definition, such representational content would account for establishing a causal link between things being perceived, and categorical (or conceptual) references as vehicles of thoughts to the mind (Fodor, 1975). One could say that representations function similarly as descriptions: they use conceptual resources from the mind to encode properties of the world the same way than language does. While their existence and importance in theories of the mind are unanimous, the kind of descriptions that would frame such content remain an active debate (Ritchie, 2015; Locatelli and Wilson, 2017b). Nonetheless, this means that there should be a boundary of some sort that explains the modality of separation between cognition, where representational /conceptual content occurs, and perception, where information is being made available to the mind. As humans, one tends to experience the physical world made of external, or *distal*, objects, as a continuous scenery which is yet mediated by partial and abstract perceptions, starting from *proximal* objects on the retina (O'Regan, 1992; Palmer, 1999). Generally, such coherent representations of objects is explained by what was traditionally called in perceptual psychology the *New Look* (Bruner, Goodnow, and Austin, 1956). It is grounded in a form of data-driven invariance across the diverse proximal stimulations of an object that causes an understanding of continuity and objectivity for distal objects (Cassirer, 1944; Thouless, 1933). It also accounts for the capacity to identify and categorise objects across perceptual changes such as orientation, distance, or illumination (DiCarlo, Zoccolan, and Rust, 2012). An object must then be whatever does not change across perceptions. Informational theories would then posit that the content of a mental representation is, to some extent, driven by a causal link that carry information between a perceptual state and what it represents (F. I. Dretske, 1981; Fodor, 1987, 1990) but that carrying information in itself would not explain such representational content. An earlier process must then enable cognitive resources for it to happen. This idea can be found in the modular description of *early vision* by Zenon Pylyshyn (Z. Pylyshyn, 1999), arguing for a form of autonomy towards cognition, starting from the fact that perception itself is resistant to reasoned knowledge and does not improve with inference (eg. Illusions, modal completions, . . .).

While bayesian accounts of vision might already state that seeing is not a direct apprehension of the world but rather compound of inferencing upon informational beliefs from partial information (eg. (Jaynes and Bretthorst, 2003, p. 133)), the consideration of earlier visual processes allows for *seeing* and *believing* to become separable on the perception /cognition axis. This accounts for a prior process enabling the individuation, or *indexing*, of objects in the perceptual module (Z. W. Pylyshyn, 2006). In computational theories of vision, the very ability to individuate objects from a scene without regard to their properties is what allows to recognise a set of individual objects to form a pattern (Marr, Poggio, and Ullman, 1982a) and can justify the formation of invariant knowledge for particular concepts (Palmer, 1999). Followingly, the act of indexing can be seen as purely data-driven. Some properties in the proximal stimuli are causing indexes to be assigned similarly than what causes photoreceptive cells to fire regardless of what the visual system is looking for and regardless of representational content. Several theories about *objecthood*, or *proto-objects* point towards common claims that prior to the encoding of any sensory properties, the visual system must establish a prior contact of primitive and prototypical nature (Scholl and Pylyshyn, 1999; Z. W. Pylyshyn, 2000). Whether concerning *deictic codes* in visuo-motor coordination of gaze for primary means of referencing (Ballard *et al.*, 1997), a purely data-driven indexation of primitive properties as visual indices (Z. Pylyshyn, 1998), or *object files* allowing for storing and accessing properties needed to link the mind with primitive visual objects (Kahneman, Treisman, and Gibbs, 1992), all converge to ***a primitive causal connection which needs to exist between thoughts and things*** * ***and account for perceptual content as pointers of the non-conceptual kind*** (Z. W. Pylyshyn, 2000; Chadha, 2009). At a more transversal level of understanding the informational ascent towards building mental representations, a theory of *coherence* would explain that, only after the existence of proto-objects, can happen the establishment of representational content and coherence throughout discrete information in order to maintain a stable relation with objects (Rensink, 2000). The proto-objects yet remaining volatile at prior levels and being constantly reconstructed (see Figure 14).

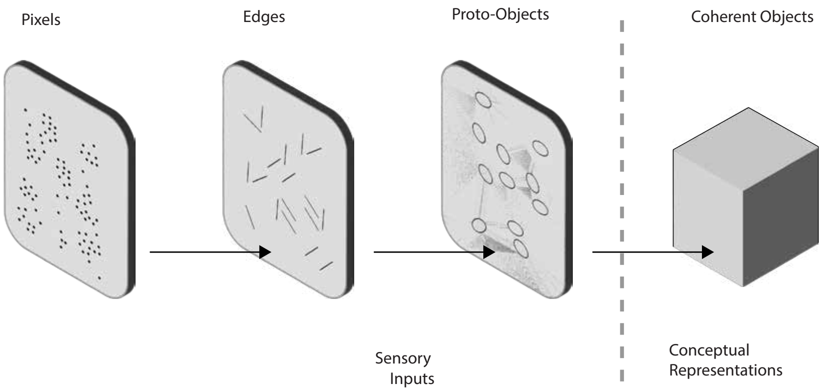

Figure 14: Diagram of early visual processing stages prior to establish mental representations of objects. Proto-objects are rapidly created from basic features (eg. Edges) and made available to feed coherent representations across partial information. Source: Rensink, Ronald A. "The Dynamic Representation of Scenes." Visual Cognition 7, no. 1–3 (2000): 17–42.

In a wide aspect, proto-objects theories follow a *gestalt* tradition of experimental psychology, where a *figure-ground* theory would intend to explain the detachment of individual figures from a ground picture (Koffka, 1935). But this early form of individuation necessarily implies certain informational constraints prior to the involvement of cognitive resources, where the number of these links between objects and symbols become necessarily limited and constantly reallocated (Z. Pylyshyn, 1989). The research on visual routines explaining the basic operations necessary to build characteristic visual patterns (Ullman, 1984) was later reused to explain that early individuation, or *subitizing*, involves the tracking of individual pointers (Trick and Pylyshyn, 1994) with a general threshold of 4–5 simultaneous subitized indexes before subsets are being performed. Known as the *multiple objects tracking paradigm* (MOT), it led to the discovery of important information about indexing mechanisms (Scholl and Pylyshyn, 1999; Pylyshyn and Storm, 1988) and showed that the tracking of individuals could be performed independently from visual properties and yet keep track of their numerical identity, or *numerosity* (Z. Pylyshyn, 1989). In that sense, ***numerosity becomes an essential feature of proto-objects prior to repre-*** * ***sentational content***. It is yet unknown which kind of features are engaged in early vision and perception more generally, but there is a limited set of basic features restricted to properties that can define visual surfaces and that can divide one texture segmentation from the next one. So it is assumed that proto-objects can be formed by such cluster of basic features (Wolfe, 1994, 2007) which are competing for a pool of available indexes (Leslie *et al.*, 1998). These features are generally considered as *quasi-sortals* because they already have obtained a location, are countable and can be tracked (eg. an edge). Once past that prototypical stage, objects are not clearly individuated yet but already allow for conceptual reference of a *protean* nature

(Clark, 2004). Between more than just its features and less than a distal object. While these processes are still very early and benefit from a high degree of autonomy towards cognition, their existence are posited here as necessary to enable representational content to happen. Their modulation regarding the facilitation of segmenting feature clusters might support the subsequent modulation of object references (Wolfe and Horowitz, 2004; Wu, Wick, and Pomplun, 2014). The degree to which early vision is encapsulated and detached from cognitive processes remain an important discussion specially regarding its capacity of interfacing a correspondence between proximal and distal objects (Echeverri, 2016). However its formalisation evidently provides for a useful basic instrumentation of early perceptual mechanisms.

2.2.2 *When Language Becomes Operational*

A general assumption for the previously mentioned early visual processes is that they are key in interfacing information ascending from the *bottom-up* (ie. from proximal objects to representations of distal ones) with information descending from the top-down (ie. early cognitive processes building causal links between both types of object) (Theeuwes, 2010). This idea assumes that two kinds of temporal agencies must be at play to allow such duality. And while early vision of the perceptual kind has its processes coded at the time scale of biological evolution (Nilsson, 2009; Nilsson, 2013; Hubel, 1988; Hubel and Wiesel, 2004), an early cognition would necessarily show a temporality at the scale of conscious operations which are both phenomenal and not (Block, 1990; Chalmers, 1997). Disregarding the concurrent temporal agencies of perception and cognition would lead to generalise the lack of boundary between both, and looses the systematicity advantage (Tacca, 2011) of early perception, as in (Clark, 2013). In regards to the present research, another motivation to stick to the idea of such boundary can be clearly stated. This form of articulation generating powerful and fundamental capacities related to intelligence can easily find an architectural correlate in what is generally called architectonics and also drives fundamental questions about modeling in architecture. Since it follows a data-driven ascent to reference objects, the proto-object paradigm also assumes that what precedes early cognitive processes must be necessarily free of semantic content, or *language-free*. It is often assumed that descending cognitive events have effects on their perceptual inverse (Collins and Olson, 2014; Dunning and Balcetis, 2013; Goldstone, de Leeuw, and Landy, 2015; Lupyan, 2012a; Stefanucci, Gagnon, and Lessard, 2011; Vetter and Newen, 2014). But while there are obvious effects on the post-processing of percepts to the mind at higher levels, it does not automatically imply a cognitive penetration into the perceptual module at early stages (Firestone and Scholl, 2015). A general phenomena must then serve as a *salient* joint of some sort articulating both worlds. This assumption is more generally known as the *binding* problem (Rosenblatt, 1961; von der Malsburg, 1981; Treisman, 1996; Roskies, 1999; Herzog, 2009). Proto-objects must be causally linked with particular concepts in order to relate to distal objects and make sense of the world (see Figure 15). And even if according to the aforementioned LOT theory, language might not be the overarching structure that organises thought processes and which primitive blocks are concepts (Fodor, 2008), its role is key in formalising particular causal links because of its involvement in informational descent and the phonological, visual, and semantic levels at which it occurs in a sort of *mapping* (Huettig, Mishra, and Olivers, 2012).

Two important research paradigms question that idea. The *visual world* paradigm (Cooper, 1974; Tanenhaus *et al.*, 1995; Allopenna, Magnuson, and Tanenhaus, 1998) that is generally modeling such binding when language utterances are being imposed on attended visual scenes (Huettig, Rommers, and Meyer, 2011). And the *visual search* paradigm (Wolfe, 1994; Egeth, Virzi, and Garbart, 1984; Treisman, 1988), where pre-specified semantic targets are supposed to guide the search of a visual scene in order to bind visually salient bottom-up features and top-down intentions (Wolfe, 1998). While these two main paradigms place the visual scene and semantic cues in different temporal orders, both entail their observations under the phenomena of *attention* (Huettig, Mishra, and Olivers, 2012; Carrasco, 2011). Being at the threshold of the binding problem, attention does not sit well in a categorical distinction of conscious or unconscious events but rather serves interactions of gradual conscious dependencies which also work in varying temporalities (Montemayor and Haroutioun Haladjian, 2015). However, the binding of language and visual features is necessarily observed throughout its manifestations.

During his creative investigations into the cognitive mechanisms of the mind, Paul Valery ventured in the hypothesis that attention was crucial in the creation of meaning (Valery, 1974).

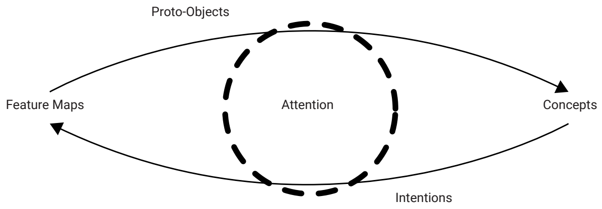

Figure 15: Schematisation of the relationship between both ascending and descending processes binding perceptual features with representational content. Taken by both ends, feature maps representing proto-objects and concepts from which derive intentions, the role of attention in the building of representational content is a salient joint articulating both.

In the *feature integration* theory (Treisman and Gelade, 1980), attention becomes the mechanism that encodes information. Something that is also considered necessary in the general theory of *coherence* (Rensink, 2000) in order to maintain representations. It is now well known that perceptual inputs are never synoptic, and the integration of information necessarily happens within discrete operations. One way to observe and understand this in the visual field is through the observation of oculomotor events. There, information becomes integrated into representations by saccadic eye movements (Henderson, 1997). And these trans-saccadic movements allow for the retention and integration of information from one visual fixation to another (Irwin, 1991). Given that there must be at least three basic steps allowing for visual fixations (selection, engagement and disengagement from the attended location), it feels logical to also understand visual indexes as a pre-condition to support the entire process (Z. Pylyshyn, 1994; Pylyshyn, Burkell, *et al.*, 1994). Since the early works of Alfred Yarbus (Yarbus, 1965; Tatler *et al.*, 2010) and Michael Posner (Posner, 1978, 1980), attention has been shown to occur also covertly, outside of consciousness. Which led to the understanding that both semantic and non-semantic representations happen to be encoded. Both visual and linguistic inputs subsequently overlap at higher levels and reinforce each-other (Theeuwes, 2010). However, whether attention is guided by semantic intentions or not, attention remain widely considered as pondering both cognitive and perceptual resources to build meaningful representations. ***If there is little to act on the formation of proto-objects except by facilitating their segmentation, their is much left to act on regarding the articulation of both pre-specific content (or pre-attentive, pre-conceptual) and representational content (or post-attentive, conceptual and intentional) by modulating attention itself. Additionally to stimuli manipulations, intentionality can become such active agent of modulation.*** *

But given the pace of these processes, one must reflect on basic and operational aspects of language upon attention. Or intend to recognise what type of language may support the articulation of information at this stage. In the philosophy and psychology of language, the assumption that the emergence of meaning of particular words (or concepts) can be traced throughout the operations of intentional states (Ceccato, 1965) is something that led to the development of *Operational Linguistics* (Benedetti, 2016) and more precisely at the level of attention, *Attentional Semantics* (Marchetti, 2015). The interest and main argument of these language models being *operational* relate to their lack of dependency with syntaxes and the lack of autonomy of language in general towards meaning regarding its emergence in cognitive events (Benedetti, 2016). In such sense that they would only seek to explain the abstract level at which semantics may become operational at early and volatile phases of meaning construction. These approaches encompass basic levels of semantics, where concepts can be addressed directly by basic stimulations and necessarily infer on dynamic articulations.

2.2.3 *When Representations Become Transient*

As with virtually any cognitive process, the interactions between language and eye movements necessarily involve memory (Huettig, Mishra, and Olivers, 2012; Pashler, 1998). Since there must be a place that holds for such capacity. But it might become useful to detail what type of memory is involved more specifically at this point of articulation. In a broad understanding, memory is divided in terms of duration and information chunk size capacities (Cowan, 2008). Where Short-Term Memory (STM) stores and processes information decaying as a function of time, and in limited chunks, in order to provide for fast processing of perceptual inputs. And Long-Term Memory (LTM) would be responsible for storing and processing conceptual resources. Although there are significantly diverse taxonomies of the object of memory depending on the causal mechanisms to observe; should they be focusing on scale, hierarchies, content, phenomena or descriptions (Werning and Cheng, 2017), the main interest being followed lies in locating generally early forms of compositionality under attention as emerging structured representations (Werning, 2005, 2012).

Followingly, what is traditionally called the Working Memory (WM) would be close to STM and depend on its considered relation and sensitivity to attention (Cowan, 2008). A primary mechanism defining WM is thought to be the execution of controlled attention (Postle, 2006; Cowan *et al.*, 2005). Targeting, sustaining, and disengaging attention in feature clusters modulates the span of maintained early representations into WM. Although attention directed at mid-level sensory areas of the brain appear necessary, or even sufficient, for such representations to enter WM, information of a more abstract and conceptual sort can be bound into them through a process called global broadcasting (Kosslyn, 1994). WM is then considered
* as the place to hold for ***fleeting sensory-conceptual representations***. LTM and especially its episodic component is intimately related to the presence of conceptual content at this point, which are considered as activated long-term memories for a short period of time(Unsworth and Engle, 2007). Some hypotheses go to the tight relation of WM with motor processes and assume that it would be resulting from the evolution of forward modeling processes of actions initiated from motor control necessities (Wolpert and Ghahramani, 2000; Jeannerod, 2006; Carruthers, 2013). While WM is posited to hold for the prime access of early representations to consciousness (Baars, 2002), it is also widely accepted that following STM constraints, WM can hold several items but is quite limited in span and size (Cowan, 2001). There are nonetheless significant and stable individual differences in WM capacities which support comparative performances in many other cognitive domains (Engle, 2010) and account for most variance in *fluid* general intelligence (Kane, Hambrick, and Conway, 2005). Such studies underlying functional models of memory allowing for learning, remembering and forgetting were initiated at the end of the 50's (Scoville and Milner, 1957). Given the duplicit account of WM, it would be hard to not understand that the transient state in which representations are held there, is not initiated by a single end but both perceptual and cognitive inputs. In that sense, ***it is there***
* ***that memories start fleeting and representations become transient***. Over the past decades a more precise theory was developed to study the dual presence of such content at early stages under attention: the *Conceptual Short-Term Memory* (CSTM). It posits that the rapidity at which a stimulus may reach a *post-categorical* representation within less than a second onset and that such representation may amount for further structuring or rapid forgetting is largely occurring outside of awareness. It must therefore be present in early components of memory allowing conceptual content to establish particular meaning onto basic representations (Potter, 1993, 2012). This kind of capacity is clearly identified under the serial presentation of stimuli, where their semantic encoding from repetition and differences can be compared (Coltheart, 1999).

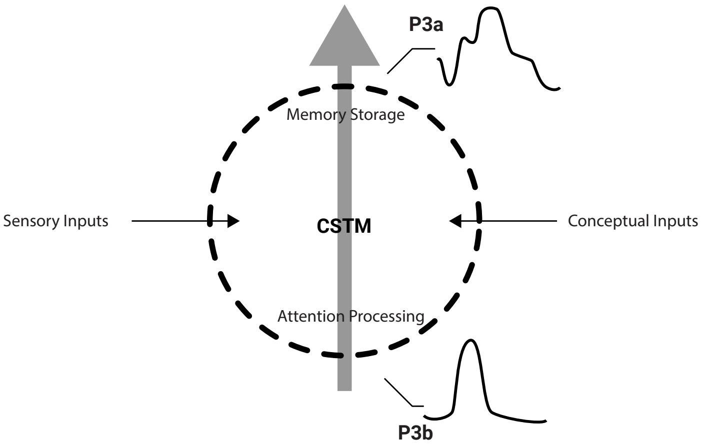

Figure 16: Diagram Combining both views of the CSTM and CUT theories. CSTM holds as the place enabling the capacity to gather both sensory inputs pre-structured as feature maps and conceptual resources activated from LTM. The attentional processing that leads to further memory encoding of meaningful proto-objects into representations of higher cognitive levels is indexed by ERP phenomena. Among which the two main subcomponents of the P300: P3a and P3b, mark the boundaries.

Interestingly enough, such theory correlates with phenomena found in studies of electrophysiology known under the name of *Context Updating Theory* (CUT) (Polich, 2007). It argues that peculiar brain patterns may serve as index of revised mental representations induced by incoming stimuli (Donchin, 1981a; Fabiani, Karis, and Donchin, 1990; Kok, 1997; Rushby, Barry, and Doherty, 2005). Once a sensory input has been received, an attention-driven comparison must occur between prior representations held in WM and the feature clusters of focus. If no feature change is detected, the currently held representations (considered here as the *context*) are maintained and only sensory activity are being considered as evoked. Otherwise, the context is being updated by the encoding of novel information and peculiar neural phenomena occur. These phenomena are mostly grouped under the term *Event-Related Potentials* (ERP) and one component is particularly studied to that end due to its temporal location at around 300 ms onset stimulation: the P300 (Kutas, Kiang, and Sweeney, 2012). A first report on observing what is now commonly called as the P300 wave appeared in literature around 1965 by Samuel Sutton and his colleagues (Sutton *et al.*, 1965). Stimulus presentation generally elicit P300 components to their re-occurrence that are larger than those from items not formerly presented (C. Guo *et al.*, 2006; Smith *et al.*, 2001). Although tasks demands can alter the outcomes, the context is refurbished by updating operations related, as the intervening non-target events engage attention to modify the current neural representation (Coles *et al.*, 1985). The CUT hypothesis is the major theoretical account of P300, although other positions have emerged and the richness of ERP should account for further sophistication of the cognitive processes involved (Mecklinger and Ullsperger, 1993; Nieuwenhuis, Aston-Jones, and Cohen, 2005).

However, as the P300 can reflect *habituation* and *dishabituation*, this ERP component clearly indexes fundamental attention and memory-related operations (Kok, 1997; Rushby, Barry, and Doherty, 2005; Polich, 1989). It is to be noted that its origins are generally understood from the great influences that Information Theory had on psychological research at that time, to study the correlation of manipulating stimulus information with the variation of physiological responses (Bashore and van der Molen, 1991). A study that will become better known as *Cogni-*

tive Psychophysiology in the late 80's[14]. Under that lens, ERP may provide insights in attentional markers of the non-behavioural kind (Schneider and Maasen, 1998). ***Such phenomena enable the indexing of most probably salient stimulations regarding subjective interpretations of*** * ***particular concepts in all their variance*** at a very early and rapid stage even before actions or inhibitions may be triggered in the virtual buffer of possible meanings that represent the CSTM. The empirical and theoretical background suggests that the P300 may stem from neural inhibitory activity that enhances attentional focus to promote memory storage. The proposed model of CUT posits that the P300 is comprised of a P3a that results from an early attention-related process stemming from a WM representational change, and a P3b that occurs when the attention-driven stimulus signal is transmitted to temporal and parietal structures for further encoding (see Figure 16). Thus, the P300 waveform may reflect neural inhibition that occurs when stimulus and task demands engage fundamental cognitive mechanisms. And it might be the earliest observation of memory retrieval driven by attention.

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[14] For a description of the emergence of the field, see: Council, National Research. *Brain and Cognition: Some New Technologies*, 1989. : link.

2.2.4 *When Volitional Content Becomes Generative*

Very often, the relation entertained between memory and architecture is of the archival type. And in lack of better common understanding, it serves as an archetypal posture towards the capacities of memory. Because, of its physical outcomes, its tangible artefacts, architecture tends to freeze events in space as a form of a tangible archive of precise moments and irreversible encodings. It points towards the very event and the way it was encoded instead of the full capacity to remember and represent it. *Remembering* becomes alienated from its essential counterpart in the dynamics of memory that is *forgetting*. While brilliantly staged in one of Jorge Luis Borges' short stories: *Funes El Memorioso* (Borges, 1944), forgetting is what enables thinking to a large extent. Without this capacity one would be incapable to relate to the world (Shapiro, 1985). This observation is also very analogous to early studies of memory performed by Hermann Ebbinghaus during the *golden age* of memory studies during the second half of the 19th c. (D. Schacter, 1987; D. L. Schacter, 2001) and which treated memory, from a psychological standpoint, as a self-contained faculty for retaining information (Ebbinghaus, 1885). While the idea of forgetting was already considered, its dynamics were still overlooked. As it will later come to a general understanding along the 20th c but can be strongly illustrated in Martin Heidegger considerations (Heidegger, 1927), the past must be pictured as a mental horizon. Necessary indeed to our capacity to remember, but revealing as well that ***the concept of forgetting is a phenomenological reminder to understand the past as an open temporal horizon from which things can be recollected in a non-conservative way*** (**carman_heidegger_2017**). *

One part of the problem arises when architectural artefacts are considered for such a remembering experience. The main failing argument from a phenomenological perspective would be to understand that because of its *constructive* dynamics, memory cannot be understood as a conscious and objective instrument of measure. Self-ascribe memory is generally understood as a *groundless* argument in the sense that its content is in no way fully consciously accessible (Naylor, 1985; Bernecker, 2010). No doubt the phenomenological experience of memory plays an active role in the modulation of representational content. For example, one might want to challenge ideas of *intentionality* over *learning* (Dreyfus, 2002). But following the developed train of thought until now, this would happen essentially through either descending processes or by accessing primitive content which has already been pre-structured as aforementioned. In short, the early and partially accessible part of memory may hold more content as potential meanings which are being evaluated and measured, in great part, outside of a conscious experience. Such dynamics and potentials would be lost if memory was considered only from a phenomenological aspect. In order to observe the greater capacities that memory may hold, a wider and more synthetic perspective is necessary. ***One common pattern that spans and binds every single psycho-philosophical approach on the topic of memory is the degree of consideration given to the volitionality of its content***. Balancing between the capacity to remember and the * one to forget. From there, appear common principles of self-decentering, multiplicity, infinity, modulation, uncertainty, compositionality, continuity, articulation between the world and the individual. These principles all gather around the basic concept of recollecting in a generative fashion and when the mind has to deal with novel information to discriminate.

As many ideas in philosophy, probably one of the strongest basis about memory rests between Aristotle and Plato as the first strong establishment of memory constituting the temporal dimension of knowledge (S.-G. Chappell, 2017a,b). The metaphors introduced in the *Theaetetus* (Plato, 2017) as the *wax tablet* and the *aviary* presented memory as marked by impressions of varied forces and knowledge as being volatile, never entirely graspable. The Meno, on the other hand, proposed a naturalistic perspective tying basic knowledge (as natural) with symbolic representations which would enable empirical knowledge a posteriori (Plato, 2006). Building upon, *De Memoria* (Sorabji, 1972) introduced the objects of *phantasmata* as being formed in memory (eg. as a mental image) in their own rights to account for a subjective experience. As an idea to hold and resist the volitionality of these phantasmata, *mnemonics* where also introduced. This idea later became of great influence for thinking about causal links and resemblance, as in Gottlob Frege's *reference* e.g. (Frege, 1892), Bertrand Russel's *acquaintance* e.g. (Russell, 1910), or Saul Kripke's *naming* e.g. (Kripke, 1980). But prior works further developed already the complex understanding of the ungraspability of memory content in its entirety. Augustine's *sensible memory* (Augustine and Hill, 1991), for instance, proposed then that mental images could not consist of accurate representations of the external reality but would rather result from constructive processes conveyed by the senses (Manning, 2017). Something that the islamic thinker Averroes further amplified to discuss *imagination* through an aristotelian perspective in his *Epitome* (Averroes, 1985). There, recollection becomes a compositional process (from basic thoughts) and an act of synthesis (Black, 2017). The associative model in the *Treatise of Human Nature* of David Hume (Hume, 1738a), bridging causally ideas with impressions, was a model which greatly influenced Jerry Fodor to further review his *Language of Thought* from an associative starting point (Fodor, 2003, 2008). As one cannot know the truth for certain, a degree of resemblance between memory ideas and the imaginary must exists but is also consciously incommensurable (Flage, 2017, 1990). Similarly for John Locke, a renewed acquaintance to priors must be made through familiarities with certain features (Locke, 1689a). *Veridicality* becomes relative to the concept of remembering. And the immediate objects of conscious perception becomes ideas.

In great extent, the way the mind deals with infinity in order to establish knowledge finds miscellaneous grounds and formalisations in the study of memory. For Bertrand Russell, the way the mind can deal with infinity is by *denotation* (Russell, 1905, 1914; Faria, 2017). It becomes acquainted to a particular concept by this process (Russell, 1910). It would take the form of an image establishing a belief to a past instance or sensible experience and by doing so, endowing the image with meaning (Russell, 1919). But as developed by Fodor, every perspective on how the mind deals with references cannot assume to fully account for a continuity of the process (Fodor, 2003, 2008). Specially if computations serve as representations. However, from an ascending, intentional, influence on memory content, the work of Frederic Bartlett can still be read as influential and serves the reconstructive and social thesis of memory (Bartlett *et al.*, 1932). Mental processes are seen as continuous in degree rather than in kind. The veridicality of a remembrance becomes largely dependent of its societal value. Following the postural schema of Henry Head (Head, 1920) and the skeptical view of Emmanuel Kant (Kant, 1781b), such value becomes context-dependent and takes part in an individual schema, active and continuously revised throughout one's mental life. In direct filiation with Franz Brentano's concept of *intentionality* (Brentano, 1874), it is a form of memory that mediates between a person and a world as an *attitude* towards the world. In such view, memory images come into being through schematic organizations. A specific point is here to make on the evolution of *Schema Theory*, which was then more tied to biophysical dynamics and therefore allowed to develop a discourse of continuity before the cognitive revolution of the second half of the 20th c. transformed it into symbolic and static computational representations (Wagoner, 2017). Another interesting aspect of memory developed along a continuity thesis is the *integrative memory* of Henri Bergson that is composed of multiple forms (Bergson and Forest, 1896). There, duration and consciousness are separated from a spatial layout to be given as continuous and heterogeneous streams of multiplicity and potentials. This continuity is then the result of a synthetic process called a *contraction memory*. An automatic synthesis of the ever-changing present (see Figure 17). A synthesis of the totality of past and present in various degrees. This metaphysical account of memory considers that forgetting produces gaps in the experience which necessarily must be filled somehow in order to act and practice reality (Perri, 2017; Lawlor, 2004). Every memory thesis that embraces continuity is evidently a non-atomistic perspective of memory. But the consideration of a necessary continuous experience of the world does not necessarily account as a totality of mental processes involved with memory. Eventually, it brings to light that this specific aspect of memory is a movement in essence and that the transformations operated on memory content have much less in common with the act of writing than the with the act of modulation in painting (Locke, 1689a).

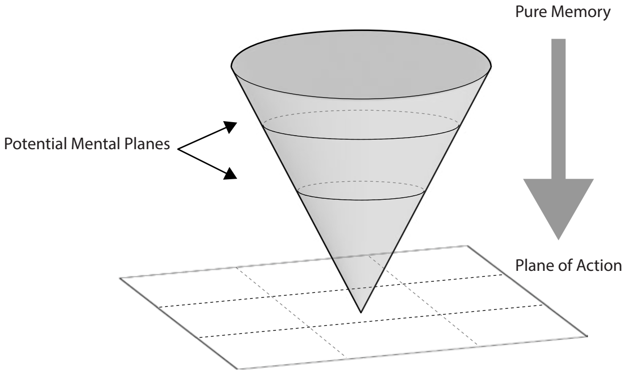

Figure 17: Synthetic overview of Bergson's metaphysical diagram of the contraction memory. The act of recollection is viewed as a synthetic process where memory potentials are funnelled across a cone. From a plane of pure memory summing every past and present, there exists an infinity of possible planes of mental states up to the apex of the cone touching the plane of action in the world. The generative power of the process is formalized strongly is this cone of contraction.

For a brief moment, psychoanalysis contributed to understand the depth of memory dynamics by confronting a historical kind with a systemic one. As emphasized by Sigmund Freud, a purely quantitative and data-driven approach would allow to discern a certain kind of structural memory (Freud, 1895). Memory content would there be the trace of events expressed by the amplitude of their imprints during the excitatory activation of neurons. And the path they take along energy flows would imprint traces as a form of differential field. Differences would then be literally taken as differences in pathways and input/output. According to this systemic kind, another sot of memory would then be required in order to deal with qualitative differences (Schwab, 2017). To extent of what phenomena are considered in psychoanalysis, this also contributed to include the unconscious levels of the mind in intentional but unconscious aspects of memory. Unconscious articulations would have to take the form of figural representations and have an agency on their own as they may recall themselves by subconscious constructive processes. Followingly, for Jacques Lacan, despite their antagonisms, the power of the unconscious imaginary lied in its symbolic order. His approach led to understand the self as decentered and balancing between subjects of different degrees of otherness (Schwab, 2017). The tension established between the self and the other is an extent of memory which also pervaded further than psychoanalysis in philosophy. For example, the question of otherness is tied with infinity in regards to memory in Emmanuel Levinas (Levinas, 1961, 1984). As a counterpoint approaching infinity and otherness, for Paul Ricoeur, the hermeneutics of the self he developed included plurality in the individual being and integrated the forgetting component of memory as a latent potential (Ricoeur, 2000; Dessingué and Winter, 2015; Dessingué, 2017). This transversal understanding generally translates to consider that in such potential, there are individual and collective aspects of memory both at play in forces that transcend the individual beyond its singular capacity. For Maurice Halbwachs, memory is primarily considered as a social collective phenomena (Halbwachs, 1950) which accounts for both remembering and forgetting. Collective memory then conditions the individual one in similar aspect than Ricoeur (Ricoeur, 2000). The multiplicity found in the individual becomes a specific echo of the community. In that regard, collective memory is defined by a particular social framework and defines the individual as *one-and-many* (Nikulin, 2017). As the collective dynamics change over one's life, so does the memory of the group in an infinite recombination. In such extended perspective, individual collective memories are incommensurable in their individual manifestations, but share common parts that allow for communication. A necessary condition also profoundly acknowledged for natural communication by Michel Serres (Serres and Bensaude-Vincent, 1989). In a sense, the conservative aspect of memory is more tied in the collective than in a purely individual aspect of recollection.

Within the wide recollection of what is to be considered as the constructive capacities of memory, it comes back to mind that, as stated by John Locke, since memory is an activity of the mind it would not be wise to primarily view it as a place (Copenhaver, 2017). In order to account for the multiple views of memory activities, it must be divided in numerous active objects which, until a satisfying unified theory of memory emerges, can allow for approaching specific mnemonic capacities. It was mentioned at the beginning of this section that memory can be seen as an active instrument of measure. It appears now that because memory is by many aspects bound to deal with infinity, the specific capacity of yet producing values in reference to specific concepts is what makes it powerful. This is what makes forgetting such an invaluable component of memory. As well as potential resource for greater variance. It is now being established that contents in memory of the non-conceptual kind contribute to the contents of consciousness. But this conscious content is fairly limited at any one time and changes as shifts of attention populate the working memory with new content, therefore forgetting a significant part of the priors (Fodor, 2008; Block, 2011, 2007; F. Dretske, 2007, 2006, 2004; Tye, 2008, 2006). In a way, on can see how discreteness, and by extent atomistic perspectives, are more bound to the finitude of cognitive resources to deal with infinity rather than an opposable term to it. It necessary to define a discrete and symbolic equivalent to it in order to become operational and computational. Empirical evidences show that rich conscious content overflows what is in the working memory and cannot be reported in its entirety (Sperling, 1960; Sligte, Scholte, and Lamme, 2008). Which provides for grounding theories of volitional content (Irvine, 2017). Classicaly, and perhaps also as a desired trait, memory is primarily understood to be preservative, to store and retrieve acquired knowledge in a non-destructive way, instead of being generative and participating to the construction of knowledge itself. In a sense that some new information might be made available to reference a pre-established relation to a concept as a form of epistemic generativity (Christoph, 2017). ***At a very general level, perception and***
* ***memory are epistemically generative*** (Senor, 2017; Boyle, 2019). ***But the generativity of memory can also be said to be doxastic in the way that one belief state can be accounted for being true***
* ***even if previous evidence has been lost*** (Feldman and Conee, 2001). ***And if such generative***
* ***capacity is intractable, it can still be observed. Therefore a computational tract can be grafted.***

2.2.5 *When Salient Features Become Parts*

Alongside the developments of this thesis, comes the understanding that the study of vision is intimately linked with the one of intelligence. The kind of relationship it accounts for in cognitive and computer science by studying natural phenomena and their computations, leads to an understanding of ***vision as a technology*** itself. It involves that perception and cognition * may be approached independently or not, that theories of the mind as well as representation models induce a need to describe adequate mechanisms to tract these relations at an operational level. Since we aim to bring back to the eye certain potentials from the mind, it seems natural to seek for mechanisms that would now take the form of inverse graphics.

The most important aspects of bringing the use of graphics in this research context is the one of *compositionality* and the way it might affect architectural modeling with computers by ***generating compositionality from code***. In the scientific advances which led to the modern * computing of information, a consequential development was also the one of the computing of its visualization. In that sense, computer graphics may be understood as the computerization of images emerging at the beginning of the 2nd half of the 20th c (Carlson, 2017). While its history may be seen as an evolution of representing precomputed information to the human eye, it also shares important chapters with computer vision, while trying to model the kind of computation vision operates about the perceived world and *naturally* complex scenes. As previously evoked, the debate on the kind of image which may hold as an analogy for representational content in the mind is still an active debate for that matter as well (Ritchie, 2015; Locatelli and Wilson, 2017b). But the computational analogy on how vision, as a technology, infers on underlying causal structures of perceived light patterns produced a fruitful approach for early vision scientists in the form of an inverse model (Barrow and Tenenbaum, 1978; Blanz and Vetter, 1999; Martinez, 2002; Lee and Mumford, 2003; Yuille and Kersten, 2006; Olshausen, 2013; Kulkarni, Kohli, *et al.*, 2015). Typically, numerous models of the visual cortex proposed that invariant representations of sensory input are progressively and hierarchically built-up through feed-forward network types of architecture (Fukushima, 1980; Riesenhuber and Poggio, 1999). And such models have been shaping the basis of deep learning in the form of *convolutional neural networks* (CNN). However, if such models may account for classification, they may not for the more complex processes of interpreting sensory information in context, or *scene analysis* (Lewicki *et al.*, 2014). And this should account, in a more symbolist perspective, for the learning of compositions from natural perception based on prior observations. This is a direct consequence of the influence of the 19th c. Physicist Herman Von Helmhotz and his idea of *perceptual inference* (Helmholtz, 1910, vol.3). To the point where early inverse approaches for the computation of visual composition have been called *Helmhotz machines* (Dayan *et al.*, 1995). Often referred to as an *analysis-by-synthesis* in pattern theory (Grenander, 1976, 1978), or *vision-as-inverse-graphics* (VIG) in current representation learning methods (eg. (Kulkarni, Whitney, *et al.*, 2015)), this allows to think in computation on how vision can be so rich in content and account for computational efficiency at the same time. An early visual model represents the generative processing of natural scenes in a *synthetic* perspective and in the style of computer graphics. Its inferential mode in the search of plausible explanations represents the *analytic* portion of the model.

While widely adopted *CNN-based* models were influenced on the previously mentioned viewpoint-invariance paradigm of the *New Look* in perceptual psychology at the end of the second half of the 20th c., other approaches such as *Capsule Networks* (CapsNet) influenced by hierarchical models in computer graphics and built upon the idea of *equivariance* (Hinton, Ghahramani, and Teh, 1999; Hinton, Krizhevsky, and Wang, 2011) started to emerge. The

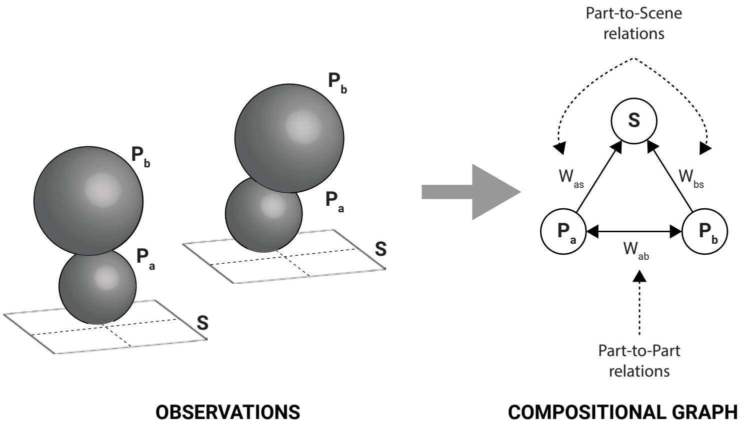

Figure 18: Schematisation of inferring compositionality from a scene. From different observations (left) containing possibly different viewpoints and possibly different instances (variable part features for Pa and Pb parts) of a scene (S), an inverse graphics model (right) would transcode equivariant properties (part-to-part and part to scene relations) into a weighted graph (Wab, Was, Wbs) to learn its invariant hierarchical composition (the generalisation of the graphic description of S). Nested and cross-modal hierarchies are possible extensions (eg. From features to parts to objects to aggregates to scene, or from features to aggregates to parts, etc...)

general principle of this idea revisits the analogy of the biological neuron, based on structured abstractions to represent natural scenes. The basic observation is that while changes in viewpoint lead to corresponding changes in neural activities of the perceptual system, the abstraction responsible for coding viewpoint-invariant knowledge is the weight of such activity and not the neuron. Patterns can therefore be found in equivariant changes of weights across multiple viewpoints and this principle brings the representational structure of an entire scene at a topological order. Structural descriptions based on weight values build up the hierarchical relations from features to salient objects by encoding these relations linearly through matrix representations. In a more generalized formulation, ***from the local topology of different parts together, one can predict the structural description of their aggregation*** (eg. The combination of the pose of of a mouth and a nose in reference to a face can predict the structure of a face). In a simplified version, the inverse problem in modeling perceptual scenes of the distal world from retinal images is the following: for a given surface projected on a 2D plane (proximal, on the retina), there is an infinite number of possible configurations in the 3D field of view (distal representation of the surrounding physical world) (Palmer, 1999; Pizlo, 2001). ***When the actual state of the distal configuration is unknown, inverse modeling must then be inferred. Because inverse problems generally contain intractability by design, they represent a proper mechanism to deal with cognitive discrimination, or the subjective attribution of meaning, under uncertainty.***

> *[...] though we assume that the mechanisms by which mental causation is implemented are in all likelihood neural, we don't at all suppose that psychological explanations can be reduced to, or replaced by, explanations in brain science—no more than we suppose that geological explanations can be reduced to, or replaced by, explanations in quantum mechanics. Confusions of ontological issues about what mental phenomena are with epistemological issues about how mental phenomena are to be explained have plagued interdisciplinary discussions of how—or whether psychology is to be "grounded" in brain science.*
>
> *- Fodor, Jerry, Pylyshyn, Zenon, 2015, Minds Without Meanings, MIT Press, p2. -*

Eventually, the next two subsections are so intricately connected that one could argue that it makes no sense anymore to divide these objects as traditional *part* and *whole*. Specially when we come to the point where developing a certain form of compositionality demands to put these terms in question. However, we will try to avoid two classical traps in the way architecture has been dealing with the idea of parts and which were reapparaised to claim for richness in the variance of parts in the *Elements* of Rem Koolhaas (Koolhaas, Trüby, *et al.*, 2014). Namely: a claim of *autonomous* architecture fuelled partly by a vocabulary of meaningless architectonic elements used as self-referential symbols (ie. an alienation of parts), and a universal claim for undifferentiated wholes through the *seamlessness* of parts (ie. a dissolution of parts). However, the hypothesis to develop here will remain atomistic and focus on transforming the vocabulary and their definition to better fit. Not everything needs to melt under the new sun, but the light may be casted differently.

One starting point to consider in terms of elements of architecture is, certainly among others, to believe that architectural parts should be understood as a given. A form of tangible reality in the act of modeling that needs to be further articulated. The question rises if such certainty is susceptible to be altered along a gradient while their value is function to probabilistic articulations. A part itself becomes a token of what it could be referring to because its description itself would not be exhaustive or stable. That is a question to consider for the part itself as well as its value in an aggregation with other which may form a modeled object. What follows is proposing and abstraction of terms and mechanisms that may allow for more fluent and variant modeling approaches. The reason we are following a specific train of thoughts stemming primarily from cognitive science in regards to the idea of modeling and intelligence is because, at a very basic level, it resonates with issues specific to architectural modeling and the cognitive processing of parts (Palmer, 1999, 1977). After reviewing how can values be ultimately coming to and from the mind, it is important to consider the hierarchical structures that precondition ideas in architectural modeling by modality and modes of activation.

2.3.1 *Parts and Tokens*

We have previously described the notable sum of work involved in the birth of architectonics, starting by the *Metaphysics* of Aristotle (Cohen, 2016), and which accounts for parts-wholes relationships as well as architectural causality. Throughout the accumulated studies on *parthood*, emerged in the 20th c. the formal logics of mereology (Casati and Varzi, 1999; Simons, 2000). It comes at no surprise that its origins also intersect in the pre-socratic domain with seminal texts of Plato (Plato, 2017, 1870), Aristotle (Hardie and Gaye, 1984; Cohen, 2016; Slomkowski, 2016; Lennox, 2002) and the neoplatonist Boethius (Boethius and Migne, 1860; Cicero, 1831). For example, the *lineamenta* of Leon Battista Alberti (Alberti, 1485) is seen to be partly infused with the neoplatonist views on composition of Plotinus (MacKenna and Plotinus, 0270) among the vast antique legacy that inspired his work (J. Hendrix, 2011). Numerous medieval philosophy ontologies conveyed this legacy further towards ideas on parthood and equally intersect with what accounts for foundations of computation and modeling in architecture. Among them, one can mention the *Computus* of Garland the Computist (Lohr, 2013), the *theories of identity* of Pierre Abélard (Spade, 1994; Abelard and Rijk, 1970; Abelard, 1954), John Duns Scotus (Scotus, 2022a,b) and Jean Buridan (Buridan, 2001), the *threefold taxonomies* of Thomas Aquinas (Aquinas, 2008), the *theory of correlatives* of Ramon Llull (Llull, 1401), the *material differentiations* of Walter Burley (Shapiro and Scott, 1966), or the *universal wholes* of William of Ockham (William and Franciscan Institute (St. Bonaventure University), 1349). The ideas further developed during the 17th and 18th c. notably with the *logics* of Joachin Jungius (Meyer and Rudolf, 1638), the *combinatoria* of Gottfried Wilhelm Leibniz (Leibniz, 1666, 1714) and the *reviewed monadology* of Imanuel Kant (Kant and Smith, 1746; Kant, 1756). In its contemporary form, mereology is seen to stem from the deep influence of Franz Brentano through the *Logical Investigations* of Edmund Husserl (Husserl and Dummett, 1900; Husserl, 1900), and forms a consistent discourse of metaphysics on what is to be understood as a part and its qualitative relations. A first mature and synthetic formulation finally appeared at the end of the first half of the 20th c. (Lesniewski, 1916; Urbaniak, 2013; Leonard and Goodman, 1940).

By then, mereology was finally founded as a nominalistic account and an alternative to *Set Theory*, which was judged inadequate to provide identities to parts in most general cases. It separated itself by not being committed to abstract a whole or to the concreteness of the parts in order to provide for generalisation, but providing instead general formal logics based on part-whole relations. By extension, and since mereology cannot assume any serious ontological restriction to the description of a part, a part may as well be a material body, an event, a geometric entity, a property, a proposition, and anything that fits the platonic definition of indivisibility through composition. As a following distinction, parts are understood rather as components when individual units are available regardless of any exterior or contextual interaction. Arguably, mereology constitutes a strong and consistent field of research regarding the contemporary understanding and generalisation of the identity of parts. However, embracing mereology full-on to look for means of architectural modeling, just as it was the case for generative linguistics, would bring the reflection to a flawed theory that only may provide for formal logics and its self-designed limitations and circularity in the identity of the objects it articulates. In fact, important limitations to its general claim may help to rebound on that matter. Starting by *the problem of structured universals*. Mereological structures cannot bind universal properties with hierarchical structures because, for example, a thing cannot be part of another more than one since a part composing a whole by multiple instances violates its identity structure (eg. a carbon atom composing a material with multiple instances). It then falls back to consider whether such things must rather be considered as components or not. But this problem exposes other cases of non-mereological relations as an obstacle to the logico-mathematical generalisation and applicability of the claim (Armstrong, 1986; Johnston, 2005, 2006; Varzi, 2010; M. Donnelly, 2011; Hovda, 2014; Johansson, 2015). Another issue that cannot give mereology a strong stand for universal descriptions of parthood touches one of its fundamental basis: *partial ordering*. This constitutes a strong basis because it encompasses the three core definitions of *reflexivity* (eg. a description of a thing is part of itself), *transitivity* (ie. part-wholes relations traverse hierarchical levels), and *assymetric relations* (ie. two distinct things cannot be part of each other) (Cotnoir and Varzi, 2021). But partial ordering also fails in cases that are touching the idea of *concreteness* such as in biology (Rescher, 1955) or buildings (Pietruszczak, 2014). In a more general overview, the case for formal logics is to become mostly self-referential and circle back to their own limitations. Or to put it another way, ***circularity is a paradoxical problem of formal logics as they become specific generalisations***. So by design, * logically structured propositions in mereology bring such identity circularities (Aczel, 1988; Barwise and Moss, 1996). A way out could then be to follow a similar reflective path than the one we have been drawing out about computation[15] and consider that the framework must account for the intractable aspect of the creation of part identities. In the case of mereology, the value of a part, its qualitative relations, are essentially linked to its cognitive saliency. By a direct effective analogy, we similarly follow previous remarks about semantics failing to provide exhaustive descriptions to concepts[16], or about anteceding logical frameworks[17].

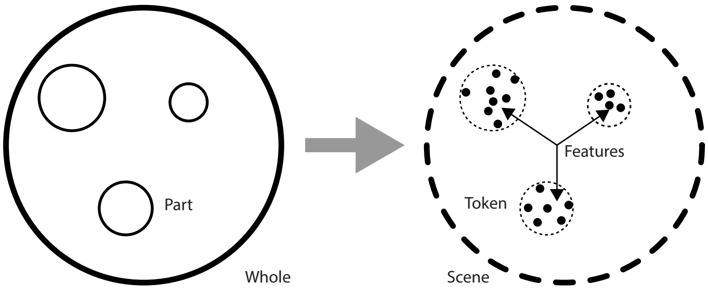

Figure 19: Transposing the part-whole schemata (left) to the tokens as bags of features in a scene schemata (right). The descriptions of parts and wholes become loose and are to be inferred upon over time.

Further details should now be added to the previously stated *atomistic* stand on the topic. Some contemporary views might assume that parts are essentially *atomeless* and infinitely divisible as some sort of *gunk* (Lewis, 1991). But atomistic views are simply necessary in all sorts of modeling. Along the logicians tradition of Jean Nicod (Nicod and Russell, 1924), Alfred Tarski (Tarski, 1929), or Alfred North Whitehead (Whitehead, 1929), architectural modeling is necessarily atomistic for productive reasons. A specific *cut* must be made into possibly infinite divisions of elements in order to provide for any capacity of articulation[18]. And that, must necessarily account for a sensible experience. On that stand, the basic vocabulary of what may constitute an eligible part for compositionality can be devised. So from the internalist theory of mind we have been following so far, ***parts must start where perceivable properties, physical features, constitute candidates for proto-objects***. Nothing being intelligible in infinity, we have *

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[15] See for example 1.4.3

[16] See for example 1.4.5

[17] See 1.4.2

[18] Here the previous remarks about the *Dedekind Cut* are being applied as a necessary operation to further think about modeling. See 2.1.3

seen the way the mind may deal with that issue in a productive way[19]. Overall, every definition of composites is, partly, generally, inadequate but, contextually, may be very well appropriate. So how to come about a generalisation of parts that satisfies our purpose for architectural modeling? For mereology, a fundamental question regards whether or not a structure has an impact on the identity and existence of composed entities. A conflictual way to look at it is through the idea of *unrestricted composition* and where composed entities exist irrespective of the structuration of their components. For Casati and Varzi (Casati and Varzi, 1999), there are mereological conditions that define parthood and indentify the part-whole relationship. A supplementation that defines the anatomy of parts and wholes from each other. But to which extent the transitivity of parthood may go? Seen through the temporal dynamics of what may come to mind as a part, it seems simply arbitrary to formally delimit the domain of what is unitary and not. For Whitehead, the abstraction of a description can only be an approximation of an epistemological perception of concrete objects (Whitehead, 1929). It does not take much time to experience and understand that a different viewpoint would produce a different unitary domain which may overlap or intersect with previous ones but cannot be completely superposed[20].

Again, we might add to the critic that this framework falls under similar issues than dogmatic ideas and their symbolic formalisation of modeling, whether they be syntactic or functional. For Levi Bryant, there is a flat ontology of objects that allows for a free movement of values among them (Bryant, 2011). As is, no object can be framed as simply constructed by another object. But a part is never a part by itself. This would account for being complete and therefore being a whole. However, this position allows to think that parts can be wholes by themselves and the whole can be a feature of the part. One can agree with such remarks of transitivity only in the view that the temporal agency of a part in becoming an object allows for reversibility. Parts are, purposefully, by necessity, in a transitional state between a pre-existing whole (eg. a brick) and being part of something (eg. a wall). Without necessarily having to specify the latter, parts contain the potential to always be in a state of becoming. Followingly, a part fails to convey, or purport, meaning if it is not put in such state. Another aspect regarding the eligibility of a part to exist in such compositional context is the degree of *intersectability* to which it can relate with others in a scene. The higher the intersectability, the more parthood is driven from the whole, and inversely. More precisely, intersections fall on the degree of commonality of gathered features (eg. several chairs would rather gain new values from what they may form as a whole. Several cats, chairs and fruits would rather gain such values from their individual or shared collective features in relation to the whole). Followingly, if there can be parts of significance without reference to a whole. So that they may become wholes themselves. And if parts cannot be considered as complete descriptions of themselves. A somewhat looser approach may still support the tentative combination of inverse graphics with ideas of the computational theory of the mind. After all, a part can still be described by its features. But as features greatly vary in quantity, quality and modality of perception, the vocabulary that one is using to progress on modeling should consider the same distinction that the philosophy of mind operated on *types* and consider that, ***the adequate way to describe the particular instances of a part is to transpose the idea of a part with the one of a token*** (see Figure 19). ***Tokens, understood as instances of a type, exhibit a form of commonality (they partially share kinds of features), concreteness (they are contextually anchored) and volitionality (they may exist only within their domain of instantiation). Similarly, components can be loosely considered as features and parts (nka. Tokens) as bags of features. Despite their volitionality, they would remain, as is, countable and therefore differentiable and directly computable.*** Specific and shared

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[19] See 2.2.4

[20] We might see in the directly following subsection how this particular aspect has been treated in the architectural developments of compositions.

values would still depend on their respective degree of intersections and autonomous features, whether intersections are provided by the scene or simply emerge from part relations.

Concepts and thoughts can also be framed as types and tokens of some sort (Davis, 2003). Thoughts, as propositions, are shareable but also are different by degree from one individual to another. In this sense, there are as many individual thoughts that there are individuals capable of instantiating an uncountable amount of thoughts about a shared concepts. In the case of language, any instance of a specific word that is subject to specificity is a token, its identity is contextual while it refers to a universal. Tokens become concrete instantiations of a universal object. At the inverse of types which tend to be used as abstract instantiations of the same universals (Peirce, 1960). By analogy, two individuals may have different tokens of the same type of thought emulated by an utterance of the like: *Grass is green*. With a word of caution, there is however a similarly problematic reliance of linguistics on type-tokens relationships than the one previously mentioned regarding concreteness (Hutton, 1990). For example, in highly open contexts as in aesthetics, a work of art and its physical artefacts cannot fully superpose as type-tokens (Wollheim, 1968; Wolterstorff, 1980). Often a type is misunderstood as the set of its tokens (Quine, 1987). Which would be problematic because a type is to be differentiated from a class (defined by its members and its cardinality) or a set (eg. defining an empty set). In contrary, a type may be simply defined by the intersections of its tokens, given a prior. Meaning that any type without token would be provided by a conceptual reference as a degree of familiarity to produce a difference value for the type. Eventually, a type without token
which are not tokens. Meaning that a thing may occur several times without being a token and can be considered exactly the same than their type. These are then considered structural universals (Armstrong, 1986; Lewis, 1986; Forrest, 1986) but evade any form of consideration of concreteness. Tokens are concrete particulars. They have a unique spatio-temporal location. And that makes them non-reproducible by natural means of communication (ie. they cannot be perceived twice, even less imagined twice). So what matters comes down to their constitutive and observable features to formalize intersections and differences among them. Tokens never match perfectly or superpose but rather intersect at least by their familiarity to a type (Wetzel, 2002). Which may call for inferring on tokens to induce a probable type. Ordinary induction from tokens would build probable descriptions of their type (Wolterstorff, 1980). This is generally referred in tradition to the *Platonic Relationship Principle* (Bromberger, 1988) and where a type functions as a unifying object. It has properties of some of its tokens but in an intractable and spectral fashion (Wetzel, 2002, 2009). A type is logically dependent of its tokens and tokens exist as independent priors until enough intersecting properties are found (Stebbing, 1935). In retrospective of the general nominalist point of view that traditionally grounded the ideas on mereology and structured linguistics as such (Goodman, 1977; Sellars, 1963) universals may exist without concreteness and can be addressed by a potentially infinite amount of specific things, given that their co-occurrence produce relatable intersections. Additionally, and in order to avoid further compositional structuration, the previously mentionned use of casual linguistics may offer the hypothesis that such generalisation is possible to serve expressivity on the basis of contextual affordances.

2.3.2 *Assemblies and Aggregates*

In a similar gesture than the consideration of parts, by reticulation, the formation of modeled objects through the articulation of tokenized parts cannot be considered as an mere assembly. Meaning that both hypothesis of either a top-down or bottom-up modeling approach are now unsustainable. But ***if we follow the idea that composition is a work of the intellect, as we believe, then producing meaningful articulations from a scene is a feature of the mind*** and we can look into better approaches.

Generally speaking, there is an intrinsic positivism in the way an object is being modeled. That is because the description of an object is linked to its composition, even so when it is only described by its lackof (eg. vacuum). So if linear hierarchical models are grounding their descriptions, their modeling would be consequently driven by assembly logics. In a way, we have seen in the past two centuries an intricate relation between the modern development of part rationalisations, together with the computerisation of their manufacturing and design. Industrial compositional logics played an important positivist role in the final way possible means of modeling where made available. There must necessarily be a market for a whole, a building, so building modeling must be regulated in a way that comes with the regularisation of parts. Even though we have seen efforts in the industrialisation of non-standard logics, building models remained casted into industrial assembly logics at a computerized level. As an example of that period, Greg Lynn criticized modernist assembly logics at the end of the 20th c. which exhibited sequential modes to great extent (Lynn, 1999). There, the figure of the curve became an image of negotiation of parts in continuum but without actually expressing the part, only through a function operating on the whole as a synthesis. But a more sophisticated relationship between the synthesis of the parts and the synthesising entity must be reappraised, following the critical account of Lars Spuybroek about the sympathy of things (Spuybroek, 2011). Compositionality is a fundational idea that precedes the one of styles in architecture and was anchored in active debates in France and Europe before reaching US between the end of the 18th c. to the 20th c.. The rich debate about compositionality in architecture was always akin to formalize syntaxes of some sort prior or posterior to the affirmation of new, borrowed or reappraised vocabularies (Lucan, 2009). A desire to cultivate architectural expressions beyond perpetually renewed limitations, as well as an obvious behavioural trait to reduce cognitive costs by externalizing and stabilizing hierarchical structures.

Yet among these reflections, should be found adequate vocabularies which do not require static formal expressions. By the end of the 20th c., the architect Oswald Mathias Ungers, among many others, recognized a continuity in history and urban contexts that makes identity, and from which an infinity of transformation may be deployed (Ungers, 1981; Koolhaas, 1972). A position also in phase with Aldo Rossi who thought the city as the *theater of memory* (Rossi and Eisenman, 1966). In such *analogue city*, buildings are purport of memory and information. But their dimensionality and agency go beyond their physical proxies. To a clear point that most architects keep in mind: buildings can hardly frame such values. At best they may evoke and emulate. Through this lens, one can reappraise the comments of Peter Eisenman about Rossi's work as a vision of another potential reality (Rossi and Eisenman, 1966, pp. 3–11). Or even better framed by Manfredo Tafuri who made a contemporary interpretation of Piranesi's vision of the city. There is no pre-specificity of the place, of space, of center and language as a principled organisation of the world. The vision there becomes *heterotopic* (Tafuri, 1987). Finitude and totality are no longer part of the architectural vocabulary and city is better envisioned as an *intellectual montage* (Tafuri, 1969). From a rather psycho-physiological point of view of history and philosophy at the end of the 19th c., one cannot help but think this critic must be infused with influential reflections of european thinkers such as August Schmarsow who saw space becoming envisionned as a cognitive process by which spatial images are built over time (Schmarsow, 1894), and Alois Riegl who positioned the observer as a compositional synthesizer(Riegl, 1893). It would then be worth reconsidering the *circularity* in the intellectual act of modeling between parts and wholes already mentioned by Andrea Palladio (Palladio and Cabiati, 1570) and look for its reminiscence in what already founded the core of mereological reflections and what pervaded throughout architectural discourses. Followingly, for Husserl (and therefore Brentano), the whole is not studied through an aristotelian completeness, but the relations between parts (ie. Composition). There, ***the whole becomes composite. And through the consideration of temporal dynamics, it is always in a becoming state gathering possible parts and potential wholes through a concept (or figure) that is external to the whole itself*** * (Husserl and Dummett, 1900). This also brings along the idea that a whole, in the extent of such dynamics, may be persistent to sparseness and incompleteness. In a strangely reminiscent aspect of albertian ideas, the philosopher Christian von Ehrenfels envisioned a whole that may exist independently of its parts and their sum, rendering it potentially fragmentary while still capable to refer to its ground concept (Ehrenfels, 1890). Mentioned as the *first ehrenfels criterion*, the whole is more than its parts. Variations would also show a certain autonomy towards the whole and form the second criterion: a figure remains the same while changing. Transported in the geometric domain, one can see how close that is to the presocratic notion of *invariance by variation*. Eventually, the unfolding of thoughts on compositionality in architecture never really fell far from such core ideas.

It would be almost anecdotal to comment on the claims of the art critic of the 17th century Roger de Piles, that the very term of *composition* was an invention of painting that later came to architecture (Piles, 1708), if we had not previously described its characteristic way to deal with continuity through modulation[21]. Since painting had its own means to deal with irregularities, multiplicities and uncertainties, it does not come as surprising that modulation was a perfect fit as a transformative act to unify differences. Ultimately, the goal being seen as an attempt to transcend and escape composition, and an endless task of the mind and the body (Bois, Cowart, and Pacquement, 1992; Bois and Barré, 1993). From an architectural perspective, the idea of composition had an extended gestation throughout multiple phases. As a strong case, the work of Leon Batista Alberti (who studied mereologic rules through the idea of *concinnitas*) developed studies of delineation, composition and light reception first in *De Pictura* (Alberti, 1435), while the later *De Re-Aedificatoria* (Alberti, 1485) was yet absent of a formalisation of composition. According to Jacques Lucan, *composition* was a term that first came out of the sophistication of the term *distribution* in the 18 c (Lucan, 2009). By then, distribution started to become directly affiliated to the organisation of the insides, the *rooms* (Blondel, 1737; Laugier, 1753). While a vitruvian distinction was made between interior and exterior room distributions, a principle of continuity was already present where every scope (ie. architectural to urban) and scale of element (eg. column, room, street) was comprehensible within a composition (Guadet and Paris. Ecole nationale supérieure des beaux arts, 1910). It is still an aspect of modeling that went through contemporary approaches after the digital. For Winy Maas, as well as many others, the electronic city is indivisible and continuous. There is always an inside viewed from someone somewhere (Maas, Rijs, and Koek, 2006). The difference would be the multiplicity of viewpoints which coexist nowadays and deserve design considerations. Somewhen halfway to its contemporary understanding, the intermediate idea of *disposition* came along in the 19th with the formalisation of european grammars. For Jean-Nicolas-Louis Durand, it became the principle object of architecture and its teaching (Durand, 1805), the art of arranging according to generalised usage. Concurrently, an intent to differentiate both *distribution* and *distinction* appeared in the 19th c. (Reynaud, 1867) and *disposition* became superposed with *composition* (Guadet and Paris. Ecole nationale supérieure des beaux arts, 1910). For Antoine Quatremère

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[21] See 2.1.5.

de Quincy, *disposition* assigned place and usage to a thing, giving it identity (Antoine, 1832) and *composition* gained the status of higher levels of abstraction in design. From there, *composition* started its contemporary journey as a generalized term in architectural modeling.

A journey that has to deal with the antagonistic ordering of entropy. Eventually, one can say that Durand can be seen as the one who stabilized composition as an architectural act from that epoch(Durand, 1805). For Kenneth Frampton, Durand proposed a methodology of universal construction in counterpart to the *Napoleon Code* (Frampton, 1980). Motivated by simplification and systemization, building programmes became species of different varieties ranging from general /universal to local /specific. Which brings his contribution to have systematized relations between parts and wholes. The didactic methods of Durand where laying on the principle of rather learning the mechanisms of composition instead of architectural vocabularies, mostly through combination and assembly. Already there, existed a strong analogy between the sought power of these mechanisms and the one of organizing language and thought. But it remains that ***the intractable part of the art of composition was in the very*** * ***synthesis of combining and assembling***. Even though rules were in place, the vocabulary of an assembly into species had to pass through natural communication and its experience. It is in that sense that the work of Durand at the *Ecole Polytechnique* takes momentum as powerful didactics for architectural education. By then, the traditional idea of *parti* was the term used to mention the intractable aspect of making a driving decision of what part would lead the rest in the process of composing. Among the infinity of choices left within the rational designs of the beaux-arts, a specific cut, would have to be made and was celebrated as the irreducible quality of a composing architect. The pre-specific condition to composing. This term took further significance in the importation of the french system in the united states in order to make the by-then tacit vocabulary explicit and intend to transcend its rationality (Ferran, 1954; Rowe, 1976; Atkinson, 1926; Hamlin, 1952).

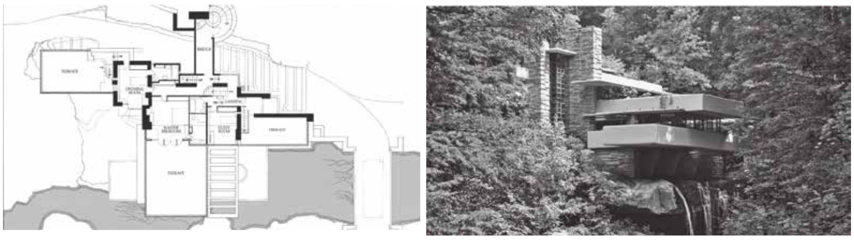

Figure 20: Schematic drawings of Frank Lloyd Wright designs of the Kaufmann house (Fallingwater house) built in 1939. Left - Second Floor. Right - Elevation Photography. As a typical example of his ideas of organic modeling, Wright does not place any centrality to organize activities or elements but rather achieve coherent modeling by aggregating them altogether. There is barely a center to be found that is not occupied or dissolved. And one cannot really speak of elevated facades for such aggregated wholes either. Sources: Adelyn Perez. "AD Classics: Fallingwater House / Frank Lloyd Wright" 14 May 2010. ArchDaily. Accessed 11 Aug 2022. Knight, Caroline. Frank Lloyd Wright. Parragon Publishing, 2005.

Symmetry, for a long period of time, was an underlying vector of organisation in the 18th c. and 19th c. but never completely affirmed or explicit. It was part of a tacit and collective evidence stemming from the legacy of *distribution*. It preconditioned the beautiful and great shapes through rationality and which brought forced symmetries as a systemic relationship and regressed the idea of composition towards an assembly serving a whole (Lucan, 2009; Guadet and Paris. Ecole nationale supérieure des beaux arts, 1910). Yet, some architects like Eugène Viollet-Le-Duc were considered more as juxtaposer than composer. Thought as an opposition to *composition*, the *juxtaposition* was seen as a regression to medieval techniques that were negating symmetry (Hautecœur, 1948; Gromort, 1938). But the appeal for irregularity by Viollet-Le-Duc in what he called *agglomeration* considered every part as appropriate in itself for a specific reason but did not escape from a *parti* or main design vector (Viollet-Le-Duc, 1863). The ponderation of weights would give a theoretic consistency to irregular articulations of parts. In brief, local necessities justified the abandon of global symmetries. A trait also recognisable in Auguste Choisy's description of *désordre raisonné* while comparing italian with french Renaissance palaces (Choisy, 1899), or as an *agglutinative* type in Henry-Russel Hitchcock's analysis of english domestic buildings (Hitchcock, 1958). Slowly, symmetry appeared as a forced aberration of overwhelmed rationalism. Where appearances must match the idea as a pre-conception and assuming that appearances are universally cast into the same train of thoughts. *Juxtaposition*, *agglomeration*, *agglutination* were some among the many points which would lay a ground for 20 c. experimentations and criticisms against symmetry that would begin to be opposed with informal rationalism (E. Pickering, 1933). For example, in the *International Style* statement of universal claim, *assymetry* is conveyed to purposes of greater appreciation, while the standardization of parts would manage to diffuse cohesion (Hitchcock and Johnson, 1932; Jeanneret and Corbusier, 1926). Le Corbusier would then redevelop ideas from Andrea Palladio where a part, an *organ*, must be whole in itself (Ozenfant and Le Corbusier, 1918). While borrowing pictural means of composition, an architectural part would become a type which must remain intact in the articulation, as an *agencement organique* (Ozenfant and Corbusier, 1968; Corbusier, 1948).

The 20th c., as a whole, is revisiting and challenging the idea of composition for the considerations of the times. For Theo Van Doesburg, the abandon of compositional hierarchies brings a universal space given by the *open plan* (Badovici *et al.*, 1926). Spatial experimentation would become *freely plastic*, *polyhedric* in space and time as an open sequence of events to explore the multiplicity of their dimensionalities. Composition is replaced by *construction* as an act of precision of such numerous dimensionalities (Van Doesburg, 1925). The increasing variations of parts develop an *optic* and *phonetic* aspect that is novel in composition (van Doesburg, 1928). Priorities shift to reciprocal relatives rather than objects themselves. Individuality becomes secondary in order to form a whole. Followingly, non-compositional approaches led to the articulation of much more complex parts comprised of activities of events as seen in Bernard Tschumi's work (Tschumi, 1988; Tschumi, Derrida, and Vidler, 1987; Tschumi, 1994). Composition is replaced by a *montage* of chaotic parts and programmes (Chevrier, 1998). Analogous to an exquisite corpse, articulations become myopic to an actual and specific scope rather than focusing on the whole that is left to open-ended descriptions in the city and the mind. Inversely, a whole becomes a singular part with its own life, once given a decoherent scale (Koolhaas, Mau, and Werlemann, 1994). Modeling become partial and episodic. Generativity and atomisation become potentials to escape from any desire of latent compositions (Besson, 2009). Retrospectively, a string legacy can be seen as formalised by Frank Lloyd Wright, where a building could not be seen anymore as a mere composition of parts but a whole bonded by force already on the verge to lose its unifying identity (see **??**). Frank Lloyd Wright (Wright *et al.*, 1928) directly attacks *composition* as a dead-end and a fallacious method inherited from Renaissance which should be replaced by *growth* from a *theme* or *pattern*. One can see there a growing desire to better the flow of design and naturalise it, just as a thought is towards is an idea. ***Architectural thought ought to penetrate the world throughout organicity.*** *

This is not be mistaken as a mimesis of the natural world but an analogy in the way values and articulations arise without prespecifications, as *plastic geometries* (F. L. Wright, 1931). Because of the necessity to deal with an heterogeneity of parts without an animist/vitalist consideration, compositional attitudes gravitated more towards the aggregate rather than the agglomerate, congregate or conglomerate. Another point that links the proverbial revisited reference of the greek temple during the first half of the 20th c., with the generally growing concern for uncertainty in compositions, is the one that grew out of the english development of the *Picturesque*. From an Anglosaxon perspective, composition played a significant role in the development of the *picturesque*. Colin Rowe denoted that the term composition appeared for the first time in UK around 1734 with the architectural writer Robert Morris (Rowe, 1974). Auguste Choisy also reconsidered the greek acropolis as a form of *greek picturesque* that further developed in the idea of the *architectural promenade* and the notion of temporal agency and procession in modeling (Johnson, 1993, 1965). The seminal work of Edmund Burke in differentiating *Beautiful* and *Sublime* along an axis of sensible experience (Burke, 1757), greatly participated in the idea of an architectural experience as a dynamic model. In the *english vision* of aesthetics (Watkin, 1941) as well as the *free planning* of english gardens promoting discovery (Collins, 1973), multiplicity of moving points were paramount in the appreciation of an architecture. Specially recognised and developed in the design of English gardens, (Symes, 1770), the idea of the *picturesque* in moving the point of experience of an individual across a scene brings the power and the means to appreciate an infinity of dispositions in the garden. Similarly, the markings of limits of the garden as a whole, disappear in english designs in order to experience variated thresholds, and the idea of a guiding horizon serves as a replacement for navigation (Walpole, 1828). Garden designs become perceptual dispositions and their values are left to individual cognitive and dynamic appreciations (see *Modeling with Neural Potentials* chapter figure 2). Definitely, english architecture of the 19th c. brought about a *culture of fragments* (Bergdoll and Oechslin, 2006) that tried to deal with the potential beauty of uncertainties. Fast forward to the second half of the 20th c. Time become fundational to perceiving architectural space (Giedion, 1941). It finally comes as a collective evidence that modeling must stem out of a synthesis of human perception as a moving point in space and time (Moholy-Nagy, 1947). Another way to deal with uncertainty in the 20th was the use of grids to express neutrality and universality. It was a formalisation, or *formless condition* (Lambert, 2001), to abstract and generalise a way to regulate and ponder articulations between parts in an explicitly quantifiable and perceivable way by offering a generic and infrastructural metric. The grid was a way to evacuate any centrality and equilibrium with the idea of repetition and render any part a priori equal and free to develop new values (Rowe, 1976). Every part needs to develop new values freely. For example, the *non-plan* was a hypothesis to discover the organisational richness of life in human societies (Banham *et al.*, 1969). For Reiner Banham (Banham, 1969), two systems were then opposed: preserving traditional architectrual values or dematerializing them. It was indeed a distance taken away from geometric and formal compositions, to go towards topological and *a-formal* designs (Banham, 1955). As seen in the described work of the Smithsons for example where topology supersedes geometry to great extents. A-formal becomes a different kind from formal compositions and informal picturesque.

At this point, it would be rather safe to say that there is no (intellectually sustainable) contemporary discourse which can claim that identity arises from pre-specific and unitary vectors. Remaining contemporary logics of unification become inadequate from their representational framing. We are no longer composing as we use to with symmetry because contemporary architectural modeling is *grown out* of our intractable minds. The legacy schemata of architects like Frank Lloyd Wright and which reticulates across centuries suggests a whole to emerge organically from timely aggregates, within which parts are locally correct and globally pondered. As-is, an aggregative process can be designed as a kind of composition as well, but one that is not ordered by a vector of equilibrium. Equilibrium, is generally an emergent phenomena from the reticulation of aggregates themselves. Many intermediate and discontinuous levels of organization must be accounted for in emerging phenomena. Therefore an aggregate has the freedom of evolving meaning from many levels and modalitiess of time, space and frequencies that classic composition cannot allow by design. This can be achieved if the schemata regresses and abstracts to both ends, where a part become a circumstantial bag of features and a whole whatever comes from the rendering of a scene, as we follow our inverse graphics schemata.

2.3.3 *Categories and Concepts*

At this point, it becomes necessary to consider the kind of objects and transformations in the mind that may support such thoughts about composition. To that end, we briefly venture into the invention of *categories*, their theories, derivatives and relevant uses. Traditionally, from an aristotelian legacy of the *logic theory of predicates*, a category holds an attributive, predicative, function to things (Bruun and Corti, 2005). Interestingly, the logical deduction of a particular predicate from a thing can easily fall into *categorically* different places. When seen as an *expression*, the study of predicates would belong to grammar. When seen as a *concept*, it would belong to psychology. And when seen as an expression that signifies an object through the use of concepts, it would come back to logic to study it (Bruun and Corti, 2005). Probably, the reason for such wide considerations across scientific fields of research has to deal, again, with the nature of its fundamental and universal claim. However, the original predicative understanding of the *Categories* reconstructed throughout the *Organon* (Aristotle, 2012) has been subject to serious alterations across centuries, starting from the neoplatonist Plotinus (MacKenna and Plotinus, 0270) by reevaluating the applicability of the categories to both real and sensible understandings of the world. Several critics and alterations followed and got transmitted across the Latin world, seriously modified throughout middle-ages, and got totally rejected by the 16th c (Bruun and Corti, 2005), to be replaced by other theories such as Immanuel Kant's (Kant, 1781b) or John Stuart Mill's (Mill, 1843) rather focusing on theories of classification of concepts appealing further to the domain of psychology. By then, the logic theory of the aristotelian categories completely disappeared and did not take part in the *fregean* corpus that will found modern logics either. From there, a category becomes analogous to a class.

However, the foundational definition will somehow partly reticulate through subsequent interests in the 19th c., as an intelligible collection of objects which unlike a class, is not countable and does not necessarily only gather shared properties (Aubenque, 1980). The work of the german philosopher Friedrich Adolf Trendelenburg allowed to reappraise the original categories and brought about a new vision of predicates as enunciations of a concept in a determined signification (F. A. Trendelenburg, 1833; A. Trendelenburg, 1846). Categories were put right at the fulcrum where a manifested thing meets with language in its intent to signify, and inspired sorts of primitive grammatical relations recognised during the late 20th c. by influential linguists such as Emile Benveniste (Benveniste, 1958). Eventually, one can nowadays understand a category as the highest generalisation of a thing that supports, *a priori*, its understanding. But since such understanding is only accessible through the cognition of phenomena, categorical structures may only be approached according to our thoughts, experience, and language. Early cognitive psychologist such as Susan Carey (Carey, 2009) have been studying the fundamental categorization of objects at early age, and which support a rather naturalistic account on the place that categories may occupy in the mind. In general, the nature of categories in the mind and their consequential aspect towards the cognition of things have been debated across cognitive science at large (Lakoff, 1987; *Early category and concept development* 2003).

On a side note, the very idea of category inspired a rather important field of symbolic representation for the 21st c. In the face of Category Theory (CT) (Eilenberg and MacLane, 1945). The appeal transpired across many scientific fields related to computation because of the very categorical and ontological, approach to mathematical formalisation, and its capacity to support greater abstraction and generalisations of concepts about informational structures (Asperti and Longo, 1991; B. Smith, 2003). CT can be briefly summed up as essentially making *abstract bridges*, functions about *objects* (holding an *identity*) and *morphisms* between them (preserving objects identities and *structure*). The basic operation framing it is called *composition* and is of the associative type (Barr and Wells, 1990). Such ideas can be naturally extended to natural communication and produce rich and promising models regarding the *efficient causalities* of architectonics through composition at a fundamentally novel and refreshing level that reappraises the nature of an invention (Zafiris, 2020). In cognitive science, it appeals to the framing of compositionality by mapping its features of systematicity and productivity[22] with the abstract morphostructural representations allowing for such generalisation at an operational level (Phillips and Wilson, 2010; Gómez-Ramirez, 2014; Spivak, 2014). Eventually, *natural transformations* in CT may also be seen analogous to *transformative thoughts* in the Computational /Representational Theory of the Mind (CRTM). These considerations of course, belong to the debate of a rather *naturalistic* account of the mind at a basic level. However, the main interest here is to identify a vocabulary of basic objects at intermediate levels of cognition that purports the categorization of an experience from the world. Where thresholds of natural communication are reachable and an interface can be built. ***In a sense, a category to the mind operates in analogy to a horizon. When in sight, it is only partly seen. And even though always out of reach (that is the nature of a horizon and not what lies there), it holds the potential to become graspable (by reaching what is partly seen there)***. In order to do so, the next basic object concerned by composition and allowing the mind for such *graspability* and understanding is a *concept*. Inversely, categories are about concepts which are not extracted from experience, but impose on them a pre-specific domain of intelligibility and compositionality. *

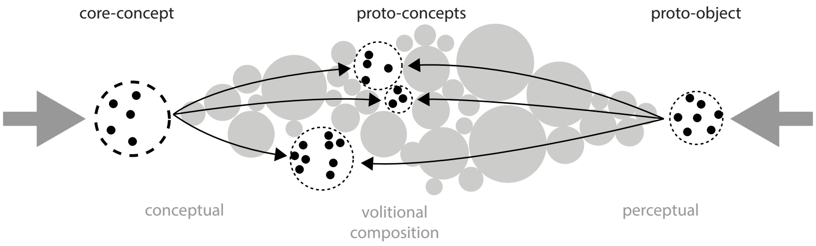

FIGURE 21: Schemata of two kinds of compositions occurring in the mind during conceptual-binding. Regarding conceptual content (Left), there might be conceptual cores and conceptual prototypes to allow for both variance and communication. Perceptual content (Right), on the other hand is directly concerned with its indexing with fleeting conceptual prototypes to allow for fast inferences. The later is viewed as a rather volitional composition with an impact over time to the core structure of concepts.

In CRTM, concepts are psychological entities that take place in an internal model of representation. Traditionally, concepts and their basic structures take a crucial role in the productivity of thought (Locke, 1689a; Hume, 1748). We have seen how theories of proto-objects[23] may construct internal symbols that enter the mental processes of *concept-binding*. Perception represents the beginning of beliefs fixations by allowing the matching of a thing in the world to an idea in the mind by proto-conceptual mechanisms. Throughout that course, concepts are considered to be the building blocks of thought and crucial to the psychological explanations of categorisation. As abstract objects in tradition with *fregean senses* (Peacocke, 1992; Zalta, 2001). From the bottom-up, differences in sensed cognitive content translates into differences in modes of representations. Classical views considered that a concept has a structural description that sufficiently conditions its components and boundaries at a core level. The acquisition

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[22] See, for example 1.4.5. Specially the comments about Jerry Fodor and his thesis of *Language of Thought*.

[23] See 2.2.1.

or recollection of a concept can be viewed as the assembly of their components. Categorisation can be seen as the matching of a concept with cognitive content by intersecting with its components. And indexing as the result from that matching and its determination. However, due to the uncertainty of an individual's cognitive content, the variance of these components may provoke totally different sets which are volitional by nature. From the viewpoint of a *conceptual atomism*, concepts are not tied to core descriptions or other concepts but rather to the world itself and what may be sensed from it (Fodor, 1998; Kripke, 1980; Putnam, 1975; Devitt, 1981; Millikan, 2000). Probably, concepts lack exhaustive descriptions *by nature*. Overall, there may very well be different types of conceptual structures that individually enable parts of the categorisation process in a form of *conceptual pluralism* (Laurence and Margolis, 1999). In a more *prototypical* perspective rooting from Wittgenstein(Wittgenstein, 1953), concepts are seen to have a probabilistic structure (Hampton, 2006). This view is particularly effective for understanding quick and early, *unreflective* judgments. Complex concepts may exhibit components in timely processes which are not present in classical structures and longer inferences.

But concepts could also be viewed as copies and their combinations of perceptual representations *furnishing* the mind (Prinz, 2002). ***Categorisation appears then as a similarity process*** * ***and conceptual formation more like an aggregative one***. At this level of composition, it would be sane to posit that natural language may become necessary here (Davidson, 1975). Because of the necessary intelligibility of the description, as volitional as it may be. Here, external communication can be inferred. This is eventually true for conceptual cores, where natural language augments and stabilises concepts in a significant way (Lupyan, 2012b). Concepts may purport *meanings* of some sort and mediate between thought and language. As a hierarchical structure, the ungraspable and abstract level of thought is accessed by a, partly, pre-specifically defined, concept. This allows for inference and the stabilisation of later structures such as language which in return allows for information and communication flows. This explains that an infinite amount of indexes may be produced to refer to partly identified concepts. Eventually, this the basic process we refer to when we try to scheme the foundational psychological objects enabling architectural thought on compositionality and incidentally architectonics. Since the modeled objects is the result of an aggregation one should straightforward consider them as aggregates as expressing the collective and cumulative reference to a particular concept/category. When one produces an utterance about a particular architectural element (eg. A column, a wall, . . .) or a compositional scene (eg. A building), what is referred to is of the categorical kind. A concept is partly formed when descriptions arise. But in the case no concept at all is provided, there is only the circular movement of bag of features referring to categories by indexing files in the mind. Categorization may occur by the indexing of concepts in an individual internal system that is open to external inputs such as language cues. Compositionality may be seen as working at many different temporalities and the one that interests us is the one with the upmost volitionality.

2.3.4 *Affordances and Beliefs*

In agreement with the historian William Whyte (Whyte, 2006) in his account of ***architecture as being experienced as communication***, and which resonates with Umberto Eco's *semiotics of architecture* (Eco, 1986), we may from now-on envision that ***involved messages are inevitably changing throughout the polysemy of an architectural experience that remains an intractable component of architectonics***. *

As extensively developed in the previous sections, If the value attached to architectural artefacts is intrinsically external to it, it does not mean that it is not possible to model a computational equivalent enabling a communication channel with it. Positing that an effective location for such application would be on par with observable correlated cognitive capacities of producing such values, *beliefs* appear to us as they fluctuate in the mind. Forming beliefs is considered as one of the most important features of the mind. They are often characterised in philosophy as *propositional attitudes* and show the possibility to have unstable basic structures while still having such functional entities and navigate amongst thoughts (Fodor, 1987; Dennett, 1969, 1978, 1987; Manfredi, 1993). Beliefs have a causal-functional role (Fodor, 1987) in the way that they represent a relation between an *agent* (typically an individual) and *mental representations* (typically internal to the individual). Accordingly, the agent would have a proposition, or a representation of that proposition, *tokenized* within the mental domain of beliefs. For the representationalist account, a particular belief is then considered as causal to a particular utterance or behaviour that expresses a local truth (Fodor, 1975; J. Fodor, 1981; Fodor, 1987, 1990; F. Dretske, 1988). From its greek etymology, *Truth* is defined as *unforgetfulness* (a-lêth-eia) (S. G. Chappell, 2014). From a memory point of view, where forgetting becomes conditional to the formation of knowledge[24], beliefs become the adequate object, or mode, to observe the modulation of transient representations in memory. In terms of recollection and the updating of a conceptual reference in the mind, a relevant experience does not need to be formalized as a recollected image with a certain degree of truth condition, but rather as fact that a belief of a particular degree is at the moment subjectively true or not in memory (Senor, 2017). To that end, beliefs are generally considered to be good candidates in correlations with inferred psycho-physiological phenomena occurring at early cognitive temporal windows. Here, ***we tend to hold a belief accountable for whatever the composition of perceptual content may provoke as an updating, and that the belief updating is causal to neural phenomena of local logical truth conditions***. *

Belief updating can be viewed as a general functional principle revealing the dynamics of cognitive categorization. Because of the volitionality that conditions its existence, it is broadly studied under a probabilistic framework (Nassar *et al.*, 2010; Stern *et al.*, 2010) where the description of a belief sums as a probabilistic distribution over observed states of discrete perceptual content from the world. Prior beliefs are transformed into posterior ones throughout the observation of novel information (Knill and Pouget, 2004; Courville, Daw, and Touretzky, 2006). In many ways, belief updating is very close to the mathematical formalisation of *subjective* and *imprecise probability theories* such as the theory of belief functions, or *Dempster-Shafer theory* (Dempster, 1967; Shafer, 1976). Despite obvious critics of its naive original form (Pearl, 1990), interesting probabilistic observations have been made concerning the nature of beliefs (Tversky and Kahneman, 1974; J. R. Anderson, 2014) and is now studied at various scales for both behavioral and physiological responses. Whether or not they correspond to a hierarchical predictive model (ie. a *bayesian brain*) in the mind (Clark, 2013; Bain, 2016), they represent the observable dynamics of one individuals attitude towards particular concepts.

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[24] See 2.2.4.

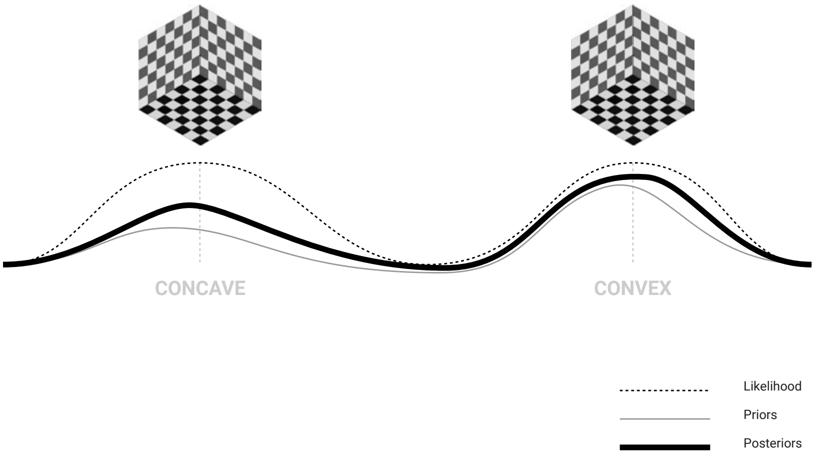

Figure 22: A schematic example of a bayesian framework. The shape of an observed object could be either mapped to the concept of concavity (left) or convexity (right). A likelihood function describes the equal probability of observations for both. Prior observations are reflected in a prior probability density function that exhibits more frequently observed convex objects. Posterior observations in similar density functions exhibit estimations as a generalized product of both likelihood and prior distributions. Source: James V Stone, Vision and Brain : How We Perceive the World, Cambridge, MIT Press, 2012, p166.

On a physiological basis at the level of an individual, beliefs dynamics may be studied in the time-frequency domain with the extensive use and repeated measures of phase-locked Event-Related Potentials (ERP), elicited by the brain upon external stimulation and resulting from transduction[25] (Sutton *et al.*, 1965; Duncan and Donchin, 1977; Sabbagh and Taylor, 2000; Achtziger *et al.*, 2014; Jiang, Wang, *et al.*, 2016). Such typical components resulting from action potentials fired by neurons have been extensively studied and correlated with the probability of specific stimulations matching currently held beliefs, their amplitude decreasing inversely to the level of expectation and relate to numerous research on *bayesian inference* (Jaynes and Bretthorst, 2003; Robert, 2007). More generally, the modulation of such components suggests an updating process that relates to the assessment of differences between a stimulus and a conceptual scene, a *context updating* (Polich, 2007; Donchin, 1981a; Donchin and Coles, 1988; Gómez *et al.*, 2019). While a basic structural unit of the brain may be seen as the neuron, * ***the action potential may be seen as the communication currency of the brain*** (Stone, 2012) travelling at conduction velocities across neural networks to exchange information. Following a bayesian brain hypothesis, prior probabilities and likelihoods are supposed to be computed by the brain before stimulus processing into belief matching (Knill and Pouget, 2004; Friston, 2005; Doya, 2007). Bayesian inferences bring novel information through differences with priors and modulate a belief both from previously described top-down and bottom-up vectors. Probably, the very capacity of forming beliefs depends on such probabilistic prior mechanisms that may take root in the theory of *affordances* (Gibson, 1986; Dennett, 2017) in a form of negentropic (Schrodinger, 1944) principle, or *free energy principle* (Friston, 2010, 2012; Hohwy, 2013), while trying to optimise internal prediction errors about states of the world and actions. However, miscelaneous studies exhibit also a lack of bayesian optimisation in human inferences due to the complexity of differential information processing in individuals (Kuzmanovic and Rigoux, 2017), and suggest that decision variance is not systematically decreasing. Accordingly, ***belief updating may be seen as a form of predictive coding when trying to index differences of specific*** * ***perceptual content with conceptual references, while dealing with adaptive variance***. Whether a belief tends to wander or be reinforced along flowing thoughts (J. Shepherd, 2019), interacting

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[25] ERP have been introduced in previous sections and are extensively described in the following chapters

at the level of their modulation may support the exploration and exploitation of conceptual content and have access to a significant level of variance and that may not be found later in the time course of our thoughts formation.

2.3.5 *Vision and The World*

Among the abundance of physiological responses produced by humans in relation to external stimuli from the world, this research focuses on the ones observable by *sensory transduction* and directly related to vision[26]. More precisely, to *visual object processing* and *navigation*. ***The utility of such phenomena of interest can be generalised by their correlation in respectively telling what things are and where they are through the process of indexing and navigating among them*** (Z. W. Pylyshyn, 2000). Two key features for the matter of modeling objects. As for their transductive modality, practical reasons dictate the way such data can be acquired and processed with computers through electrical signals. But prior to orient our view on the nature and type of data to be acquired, it is important to operate a first ***distinction between a physiological response to an occuring event as a phenomena, and its correlation with cognitive processes***. If one can observe such phenomena while studying the processing and unfolding of an event, the later does not necessarily implies to cause the former. And their correlation may not be directly linked but part of a deeper scheme of relations, or even be spurious in the worst case. At least, we know this from statistics (Galton, 1989; Aldrich, 1995) and logics (Hulswit, M., 2004). Therefore, a necessary prior step must be made to describe the cognitive processes we might want to understand and correlate with a co-occuring physiological activity, in order to not fall into oversimplified causal assumptions.

The general historical consensus throughout the developments of psychology and its subfield: neuro-psychology, is that the visual system studied in perception is considered primordial ***to construct accurate internal models of the physical world, and of things-in-the-world***. A most extensive overview on that matter can be seen in (Palmer, 1999). That is to say, in order to build mental representations of the world on the basis of information encoded by sensory receptors, and which will take part in higher cognitive processes, vision is generally considered as the main source, and processing vector, of *spatial-* and *object-related* information (Palmer, 1999, pp. 4–15). But while visual inputs are not necessary or solely responsible to build such representations, they remain the richest source of information for the processing of objects and spaces. Mostly known for discovering information processing in the visual system and describing how it constructs complex representations of visual information from simple stimulus features, David H. Hubel and Torsten Nils Wiesel layed the foundations of *Visual Neurophysiology* from the 60's on (Hubel, 1988; Hubel and Wiesel, 2004; Goldstein and Learning (Firm), 2007). Since then, vision has continued to be studied as procuring the most preeminent and accurate information on objects from a distance. While such features cannot be found combined in other senses. We could even reinforce this position by extending the argument to the case of visual impairment, as building such mental representations requires to use the very same visual system, only without the full consciouness of visual sensory inputs, and generally called *blindsight* (Weiskrantz, 1986). In the case of absolute blindness, with no perception of light, at an early or later stage of life (with little-to-no experience of visual inputs at all), it is not clear what is the role of the visual system and its becoming (Burton, 2003). But the representations remain less accurate.. For the sake of environmental awareness, we must somehow get information about what objects are present, and what events occur, in the world around us, about their locations, and even the actions they afford us. To these ends, all of available senses necessarily participate and within a much deeper cognitive framework that is *embodied*, *embedded*, *enactive* and *extended*, or 4E (Newen, 2018a). But at a basic sensory level, vision remain, in *Homo Sapiens* at least, preeminent. As it provides a specific combination of both spatially accurate information about locations and properties of environmental objects and events, which cannot be found altogether in other senses for veridical perception (Palmer, 1999).

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[26] For an overview of the variety of stimuli and physiological responses, see : Link. And for stimulus modalities, see: Link

For the same reasons and features, computer vision as a field of research and applications is almost solely focused on building such representations from digital images (Stone, 2012; Frisby, 2010).

From a strictly external point of view, the relation between optical information in the world and visual inputs in the perceptual system could be envisioned as a form of communication between surfaces. That is, of course, counting the fact that vision, if strictly bounded as a sensing model (ie. visual perception), is directly dependent of the presence of light in the environment and the understanding of photons as data carriers. The way in which physical boundaries (ie. surfaces) interact with light in the environment provides a raw structure for object's information into the visual system of an observer. One interesting way to understand the later is by encompassing an ecology of perception where the observer as well takes an active part. James J. Gibson called this model the ***Ambient Optic Array*** (Gibson, 1950) to develop * his theory of *ecological perception*. Within such array, an observer is surrounded by numerous and varied amounts of light coming from many directions and, consequently, carrying miscellaneous potential information about the surrounding environment. And the way a part of a scene is *seen*, depends as well on how other parts are (Peterson, Gillam, and Sedgwick, 2007). In addition, the very reception of such optical flows depends on the observer's capacities and position in space and time.If there were significant advances in neurobiology to find what the eye tells the brain (Lettvin *et al.*, 1959; Koch *et al.*, 2006), there were nonetheless equivalent efforts in psychophysics to find what a photon tells the eye (Hecht, Shlaer, and Pirenne*, 1941; Hecht, Shlaer, and Pirenne, 1942; Baylor, 1996). Light is understood to be of electromagnetic radiation nature (Planck, 1967; Zubairy, 2016; Nikolaevich, 2017). And the way light interacts with matter in general can be described through its *electromagnetic spectrum* (J. F. Donnelly, 2018; Buchwald *et al.*, 2020). Even though the whole spectrum is carrying information of some sorts, and in many ways interacting with the observer, human visual perception can only acquire information from a fraction of it called the *visible spectrum of light* (Sliney, 2016).

Up to this point, it would be more accurate to talk about *re-ception*, rather than *per-ception*. For there should not be any active perceptual process involved in the communication of light, from the surface of an object to the surface of an eye. However, the natural communication of light responsible for carrying information to the eye is mainly understood by laws of quantum physics (Nikolaevich, 2017; Holmes *et al.*, 2018). And ***what applies in optics and photonics should also carry some weight on how photonic messages reach the retinal surface***, and what * is their content about. At the very end of that described trajectory, the photoreceptors on the retina of the eye, responsible for the transduction of light patterns into electric signals, allow only for the intensity and wavelength of the visible spectrum, respectively by the sensing capacities of rods and cones (Tomita, 1970; Yau, 1994). So among the known basic properties of a photon (frequency, polarization, location, direction of propagation and wave phase), the eye may detect only visible wavelengths, amounts (brightness), location and direction of photons with different degrees of accuracy (Sliney, 2016). Even though each rod cell of the human eye is capable of detecting single isolated photons (Hecht, Shlaer, and Pirenne*, 1941; Sim *et al.*, 2012; Tinsley *et al.*, 2016), a subsequent electric signal eliciting neural responses is passed to the optic nerve only if several neighboring photons are synchronically detected (Manasseh *et al.*, 2013; Mannu, 2014). It is actually correct to mention that ***the only thing that an eye can see from the world is a photon***. Since the absorption of light through matter can be understood * by the particle character of the photon, and the light intensity reaching photoreceptors of the retina determines its probability to be absorbed. However, in normal daylight conditions, the overabundance of them is more adequate to be modeled as a waveform (Artal, 2016). Generally, two well known functions support the observation of both characters (see Figure 23): the *wave abberation function* is generally used to measure the absorption of light over the inner surface of the pupil and the *point spread function* (PSF) to predict retinal images from point sources. Apart from the probabilistic behaviour of light absorption by cones and rods, the projected retinal image also exhibits quantum effects and suggests ***the intrinsic probabilistic nature of phototransduction itself in vision*** (Chakravarthi, Rajagopal, and Devi, 2008). *

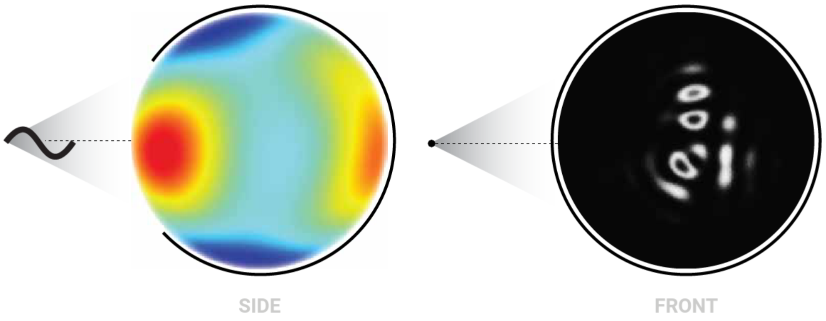

Figure 23: Diagrammatic representations of two images of light propagation, characterized by its waveform over the surface of the pupil (left), and by its particle form over the surface of the retina (right). The former is measured by using a wave aberration function while the later by a point spread function. Adapted from Artal, Pablo. 2016. "The Eye as an Optical Instrument." In Optics in Our Time, edited by Mohammad D. Al-Amri, Mohamed El-Gomati, and M. Suhail Zubairy, 285–97. Cham Springer International Publishing.

Another way to consider the modality of optical information may come from a well known question carried through the developments of geometrical optics and the way visual inputs are projected onto the retina to form a first image. Projective geometry works for the retinal image as 3-dimensional information conveyed by photons reflected by objects is projected on the 2-dimensional image surface of the retina. Since we have moving bodies, vision is a dynamic process, and the 4D structure of space-time projects to the 3D optic flow, unfolding over time, and finally to the 2D surface at the back of the eye. But the transport of optical information cannot be holistically represented solely by geometrical optics. As the field culminated in the early 17th century with the great contributions of Johannes Kepler (Kepler and Galilei, 1611), it was still struggling with the problem of the projected image on the retina (Lindberg, 1976). How come an inverted and mirror-reversed image from the lens of the cornea to the retina leads to a properly reflected image to the mind? A more satisfying, yet still uncomplete, answer only came in the 20th century with the concept of information (Z. W. Pylyshyn, 2011). It appears, at first, that such issue is corrected early-on by the brain having the optic nerves connected to the retina inverted as well and remaps information right-side up. But physiological evidences, just as geometrical representations, do not account for representational content. In fact, very little time (a few days at most) is necessary for the brain to adapt to inverted visual inputs (prior to reach the retina, e.g. invertoscope) and produce a right-side up image again (Stratton, 1897). Invariant relations and invariance in the structure of the retinal image leads to similar information, independently of its representations (F. I. Dretske, 1981; Attneave, 1959).

Another way to consider the inverted retinal image is by its non-reversible mapping to the thing-in-the-world from which light is coming and carrying information. In relation to the retinal image, the light striking the retina is generally called a proximal stimulus, and the light bouncing from things (at the location of the thing) is called a distal stimulus. As previously mentioned, the dimensionality reduction (from 4D to 2D) applied during the projection of light patterns onto the retina does not allow for the inverse (from 2D to 4D) to reproduce fully the distal stimulus from the proximal stimulus. It is intractable by loss of information. It results that a line seen from a fixed position and time may have infinite 3D configurations. An evolution of thoughts on that matter progressed from the birth of modern optics, late renaissance philosophy, to structuralism and gestalt theories to suggest that sense perception is supplemented by higher cognitive processes based on prior experiences. Vision is a heuristic process by making use of inferential rules of thumb. We have previously explained several arguments to what extent perception could be autonomous from cognition and if the whole visual system could be understood as wholly cognitive. In which case, cognition penetrates perception in various temporal and spatial layers which involves to deal with uncertainty wholly by what we know of the past. It would make somewhat, perceived visual inputs preconditioned and prestructured by prior information. The same way a light particle in conditioned by prior observations.

2.4 ARCHITECTURAL MODELING WITH NEURAL POTENTIALS

> *[...] le génie ne consiste pas à inventer de nouveaux éléments, mais à inventer de nouvelles combinaisons de ces éléments toujours les mêmes, et ces combinaisons sont variables à l'infini.*
> *trans. [...] genius does not consist in inventing new elements, but inventing new combinations of these elements always the same, and those combinations are infinitely variable.*
>
> *- Quatremère de Quincy, Antoine Chrysostome, 1788, Encyclopédie Méthodique. Architecture, Paris p385. -*

The subsections that follow serve as intermediate conclusions and prospects for the next chapter which aims to describe concurrent practical experiments. Therefore they will appear more synthetic and refer more broadly to previously developed reflections. Understanding in which domain architectural modeling is actually operational and gains significance from a more contemporary perspective of information and communication brought us to this point. Where the potentials for infinitely variable combinations are possible and can be emulated. This requires to bring architectural thinking out of its comfort zone and the space domain, in order to fully understand the discontinuity of its temporal agency and graft it back together. Probabilistic models have become extremely pervasive in science and contemporary thinking in general to the point that it could be considered as a *kuhnian* paradigm[27] without much more debate. The direct consequence on the articulations we are intending here to develop regarding cognition and architectonics in the way it is actively dealing with uncertainty and the idea of boundaries involves to frame architectural modeling itself as prototypical, since working from priors at the edge of memory. The inverse method introduced become inherently probabilistic and inferential once put in that perspective and intend to leverage both potentials of two different kinds for the modeling of intelligence: artificial and human. It is their combination, or rather *conjugation*, which should allow to overcome each other's limitations. And in a much more abstract level of thinking, find a place in expressing the power of articulating antagonistic and complementary models of thinking in order to deal circularly with knowledge and boundaries in a *demon/gnomon* association to be concurrently experimental and instrumental[28].

In analogy to the finitorium instruments of Alberti (see **??**), but centered around the synthetic and syncretic[29] point of perceptual and visual cognition, we can start to see technological potentials in forming a sort of *re-nascent* compass allowing to navigate more freely amongst information as a probabilistic probe. The kind of navigation we should now foresee is not about mapping an uncertain territory to assess its navigability but rather build instruments of navigation that provide for an orientation that is myopic at each instant while always pointing

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[27] We directly refer here to Thomas Kuhn's scientific revolutions as it became a cultural reference for largely collective paradigms in scientific thinking. See Thomas S. Kuhn, *The Structure of Scientific Revolutions*, [2d ed., enl, International Encyclopedia of Unified Science. Foundations of the Unity of Science, v. 2, No. 2 (Chicago: University of Chicago Press, 1962).

[28] See 2.1.1.

[29] See the subsection Archai and Architectonics in that chapter.

towards a horizon of significance. We strongly believe that is the proper way to leverage intelligence for its own benefits and most probably the way to update our understanding of human creativity. After all, even the *donkey of Puritan* revealed to René Descartes a provisional and myopic *moralia* in order to deal with the unavoidable uncertainty of his time (Moreau, 2012). But instead of a bare intellectual necessity, we see it as a capacity offered by computation to move forward and beyond.

2.4.1 *Architectonics in Time and Frequency*

Most common architectural discourses would start from the evidence, and without any suspicion, that architecture takes shape in space. As for most shared evidence in human societies, it raises more suspicions than certainties and could not be further away from what we know. It is most probably true that ***architecture gains stability by an observer processing information coming from the physical world and through perceptual physics, and therefore not addressing the physical world as directly causal to stable forms. And it is actually in psychophysics,*** * ***which belongs in large extent to internal cognition, that architecture gains significance initially***. And if architecture is *not concerned so much with meanings as it is with significance* (Winters, 1996), we have here our primary domain of concern. Put into perspective, it is more reasonable to say that ***there is an overarching time and frequency domain that enables the transformation*** * ***of things taking shapes and becoming objects***. Space could only account for the purport of that process, and eventually the collective aspects of its communication. From an even larger temporal perspective, images and objects exhibit their own temporality independently of linear historical time (Kubler, 1962). That works both at the extent of the history of ideas and the intent of idea formations.

We have mentioned previously a tract of thought on architecture that intuitively integrated the prototype of this idea to consider the physical object of architecture[30]. From the deployment of sensibility in a picturesque space by Edmund Burke and the opening of a landscape of experiences unfolding in time seen as the continuous aggregate of undefined events, to the modern declination of the Greek temple scenographies by Philip Johnson into a timely procession through discrete sets of architectural events, time was indeed embraced as an emulating agent to appreciate an architectural object in a kaleidoscopic fashion. Nonetheless, such prototyping did not gain much more extent in temporal agency given the following phenomenological emphasis on the physical artefacts of architecture in the built environment[31]. ***If architecture indeed takes part in the built environment, a large part of its potentials resides (virtually) in*** * ***what is yet-to-be built and its modeling dynamics***. As space does not allow for discursivity and is not the place for such capacity.

For that aspect, we can recall the transitional period of great architectural significance that crossed path with the articulation of uncertainty in the history of ideas between the late medieval, pre-modern, times, and the early humanist renaissance, during the *Quattrocento*. By then, constructions were timely and incremental. Preexisting buildings were not replaced but integrated into novel ontologies and their physical artefacts. For the historian Marvin Trachtenberg, extremely thoughtful components of architectural design thinking were systematically used in relation to the general uncertainties of the times, and which might appear analog to the temporal dynamics of the mind: a continuous redesign due to the unstable eclecticism of the period, a *myopic progression* relating to the limited capacity to overview projects on extended periods of time and subjects to periodic revisions and changing contexts, a *retrosynthesis* applied as a serial retrofit at every step due to the lack of preexisting comprehensive design (Trachtenberg, 2010). In brief, architectural design was by then intrinsically inferential, locally probabilistic and contextually updated periodically. Early iconic buildings such as *Giotto's Campanile* in Florence embody that epochal thinking (see Figure 24), where exists a clear asynchrony between the experience and use of a building on one end, and its design and construction on the other. In opposition, Leon Battista Alberti's *De re aedificatoria* (Alberti, 1485) could be seen as the prefiguration of a *modern chronophobia*, when building design stepped out of time and leaned towards modernism. In Humanist Renaissance, once *Man* became the measure of all things

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[30] See 2.3.2.

[31] See 1.4.7.

(including time), came along a transfer of significance between the positive forces of time as a collective stability, to the individual and uncertain apprehension of its passing across a continuously shortening human life duration (Panofsky, 1825; Sherover, 1975). Concurrently, while renaissance design remained highly volatile and mutating (Ackerman, 1954), Alberti integrated the circularity of time into the design itself and around the individual to establish an authored blueprint design that spans from the ideation to the realization of the building and across time. Should that idea had transpired through post-modern times, one could have reappraised the capacity of such internalised circularity in design thinking together with the positive role of duration in circular, pre-modern times[32]. Inversely, a form of *crypto-albertianism* occured where invariant designs were introduced by generalising the humanist centrality and the following uniformisation of time measures, eventually naturalized all the way through post-modern thoughts and practices, after the *modern oblivion* of temporal agency (Trachtenberg, 2010). ***Invariant aesthetics became the retroactive answer to durational aesthetics***. *

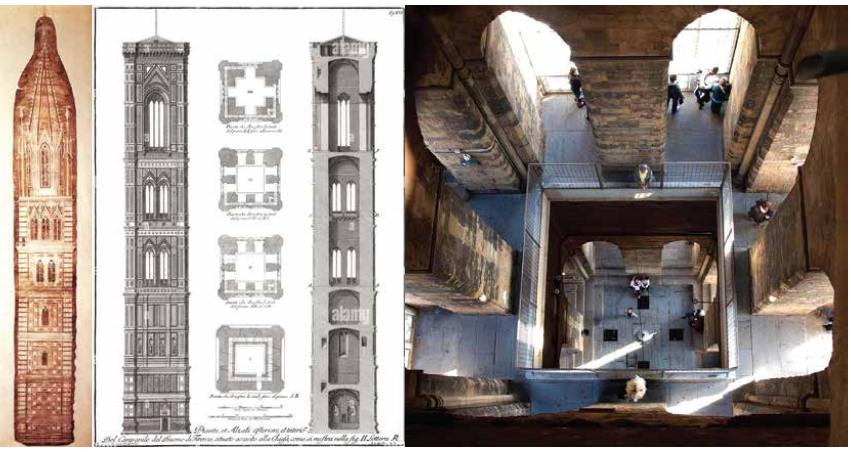

Figure 24: Left: parchment of a design sketch for the Campanile in 1334 (Source:Museo dell'Opera del Duomo, Florence)- Middle: Elevation, floor plans and cross-section after the work of Bernardo Sansone in the 18th c. (Source: Link) - Right: interior photography of the built tower (Source: Link). From design to construction, structural to ornamental elements, the campanile is composed of miscellaneous design instances in temporal layers.

Nevertheless, the evolution of philosophical knowledge regarding the temporal dimensionality of the human mind opened from the end of the 19th c. on, and might trace back from the *Confessions* of Saint Augustine in the 4th c. (Augustine, 0400). There is a powerful and intrinsic feature of memory that allows for the qualitative experience of events through time and offers the opportunity to reconsider the synthetic capacity of an individual to articulate significance in the time-frequency domains and offer a harmonic equivalent to the measure of time. One could say today without offence, yet another *bergsonism*. After all, the project for Gilles Deleuze to integrate Henri Bergson's method of intuition into his work was also partly to reappraise his vision of a fundamental generative and productive expressiveness of the human mind (Deleuze, 1988b; Lundy, 2018). For Bergson, the experience of time and its (non-objective) measure as a *duration* accounts for change and therefore the creation of values to things coming to mind. Accordingly, events are perceived through their differential temporal relations (Pöppel, 1978) and consequently the perception of spatial distances and other relations between objects follow a similar path. As we have seen previously for one primordial component of the mind[33] (ie.

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[32] Yet, an interesting association is made by Trachtenberg regarding such reappraising by Carlo Scarpa during the renovation of the Castelvecchio Museum in Verona Italy (1959–1973).

[33] See 2.2.4.

Memory) powering the concept of duration, such capacity in seen as integral to the mind itself and traverse both parts of the conscious and unconscious domains, synthesizing these deep layers into our apprehension of reality by qualifying differences. The elasticity, plasticity, of the mind that is powered by memory (Bergson, 1907, 1859), posits time as incomplete and resilient to static representations but can be grasped through its movements, changes, as a qualitative multiplicity. Formulated as a direct answer to the *kantian* thesis of transcending a certain form of freedom outside of time and space, Bergson demonstrated that duration would hold no spatial concern and remain an indivisible whole that may exhibit productivity and therefore *free will* (Bergson and Forest, 1896; Bergson, 1889). While the latter is of different, but deeply related, concerns, the productivity thesis is certainly most timely here. The homogeneous quantitative multiplicity that space may offer is put in opposition with the heterogeneous qualitative multiplicity that resists to determinitsic models and supports an individual and free movement in the experience of time (Bergson, 1889). ***Durational aesthetics, as a qualitative, uncountable experience of changes over time exhibits the productivity of the mind that cannot*** * ***be conquered within spatial domains***; to a wider spectrum of frequency than the facture of physical artefacts may ever hold. And while such expressiveness can hardly be formalised, it can be found causal to many discriminatory phenomena, offering a communication channel to such generative engine. As Deleuze reflected in his theories of imaging(Deleuze, 1983, 1985), when one quality passes to another through the intermediate of an intensive series of images (ie. external stimulations) in painting and cinema, spaces become potentiated to a higher power. This takes part in the positive definition of human creative expressions. Where expressionism is envisioned as made of two apophatic domains compound of human life: the *non-organic life of things*, and the *non-psychologic life of* mind[34]

2.4.2 *Intelligence in Conjugate Models*

A question which may now come forward for practical ends is the way we could compose with a computational framework and the intractable productive capacity of human memory in the time-frequency domain which might produce spatial artefacts with such potentials. We then come back to the idea of modeling intelligence and realise that composition would be here as well the right approach to understand the power of a dichotomic model and its own limitations in a circular fashion. To that end, we now come to consider the coupling of both artificial intelligence and human intelligence as two sides of the same coin which are sharing similarities and distinct features that might emulate each other in search of variance and novelty. A first qualitative distinction would then be to name such couple: *artificial intelligence* (AI) and *intelligent humans* (IH)[35]. ***In the sum of ideas we have previously described, these two terms result from positing two distinct questions in order to deal with infinity and the modeling of intelligence: the later (IH) asks how come a learning entity as a whole with limited computational resources may produce an infinite amount of significance, while the former (AI) tries to reproduce mechanically discrete sets of features of the mind outside of these limitations to the best of our objective reasoning***. *

These two formulations have resulted, in two different kinds of computational intelligence. From both tentative understandings come limitations and advantages which might be mutually beneficial. The characteristics of human computational intelligence are ruled by generally quantitative limitations described by the economy of biological /computational costs. The limited amount of time available for computational tasks as well as the limited amount of data being processed at all times may come from many sources. The limited availability of the task in the environment and the limited lifespan of the intelligent biological organism to acquire the data involve the development of mechanisms along different kind of temporalities (eg. biological, phenomenological, . . .) which enable a natural trade-off between exploration and exploitation of novel information in order to not only learn but also experience acquired knowledge. Such mechanisms have been largely studied and modeled for both IH and AI research eg. (Kaelbling, Littman, and Cassandra, 1998; Bellman, 1957; Gopnik *et al.*, 2017). Computational resources must be dynamically balanced because they are fixed and IH is generally considered unitary instead of ditributed as in AI. Additionally, human natural communication is limited and of the analogue type so subject to mutations in the transfer of information. Cascading effects from time limitations occur on the availability of limited computational resources and isolate its power by limited communication. AI has an inverse capacity to accumulate knowledge regardless of time constraints beyond human experiences acquired over time due to iterative methods and structured datasets. However, these limitations are also intrinsic features of the way the mind can be productive while learning from small amounts of data and produce timely structured representations. Important aspects of its computational framework have been posited and challenged such as the *computational level of analysis* of David Marr (Marr, Poggio, and Ullman, 1982a), *universal laws of cognition* of Roger Shepard (Shepard, 1987), or the *rational analysis* of John Anderson (J. R. Anderson, 1990). By filiation, in early symbolic AI literature, it was also supposed that a core feature of IH would be a hierarchical discretisation of solving tasks into subgoals (Newell, Shaw, and Simon, 1958) as a response to dealing with computational costs. Such discretisation also implies that humans have to follow heuristic strategies that result in errors (Simon, 1955; Kahneman and Tversky, 1972) but are nonetheless fundamental components of learning. Which means that these operative limitations are of two kinds: *inferential* and *optimal*. IH inferences about states of the world are myopic to one

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[35] The term was coined by Prof. Ludger during the extensive body of research conducted at the chair on AI and briefly described in 1.1 and 1.4.1. The present use of this term is somewhat interpretative in the way that it differs in its following aims.

individual, and therefore suboptimal because isolated and not absolutely guided rationally[36]. Cultural mechanisms to overrule these generative limitations have then been taken the shape of *cognitive prostheses* of some sort in the face of language and mathematics in order to encode, share and accumulate information (Boyd, Richerson, and Henrich, 2011; Henrich, 2015; Heyes, 2018). However, the compositional structure of language itself has also been seen as a limitation to an adequate transfer of information (Kirby, 2001; Kirby, Smith, and Brighton, 2004). So such mechanisms cannot account fully for the stabilisation and evolution of knowledge, neither for compositionality.

The general issue we have previously seen across many different domains of knowledge is that pre-structured knowledge is too epiphenomenal and metaphorical to be capable of characterizing thought processes and should rather be better dynamically observed as emergent structures eg. (McClelland *et al.*, 2010). There are more fundamentally basic structures that operate unitary to the mind and are responsible for this capacity. And paradoxically, it is because humans cannot instance their learning capacity in any other way than analogue transfers of information through codes, that computational learning is seen as synthetic and unitary altogether. As pieces of this puzzle, capacities for generalisation, dynamic categorisation and causal learning have been tentatively formalised under a bayesian framework eg. (J. R. Anderson, 1990; Ashby and Alfonso-Reese, 1995; Tenenbaum and Griffiths, 2001; Griffiths and Tenenbaum, 2006). In general, bayesian inference is an adequate formalism to characterise the inductive biases of IH learning on limited data and the updating of its beliefs. When there is an ungraspable object outside of the data itself that is influencing the stabilisation of a learning entity (T. M. Mitchell, 1997). It can also be understood as a form of *meta-reasoning* to develop greater generalisations in AI (Horvitz, 1991; Russell and Wefald, 1991; Lieder and Griffiths, 2020). The discriminative capacity of IH at fast pace under limited data availability and its indexing to concepts occuring continuously and under great contextual variance and sparsity of events is a feature of the mind that still eludes general models of AI. They are studied for supporting greater generalisations and the updating of labels due to its extensive prior experience. Human inference from the lens of intuitive psychophysics comes at the rescue of building coherent models of particular concepts through the discrimination of probable states of physical features and their expected impact on oriented goals based on semantic cues. The strength of AI generally lies in its generativity. It is intensively productive within bounded domains and therefore considered as pretty good function approximators. Whereas the strength of IH being extremely fast conceptual learner lies in extensive discrimination of tokens of concepts. Or to put it in a vocabulary that belongs to visual understanding, * ***IH is myopic in an unbounded domain while AI is panoptic in an inversely bounded one***. New promising models of cooperation embrace the best of both in order to advance research where generativity may increase the statistical distribution of events to discriminate at the processing speed of IH for presentation and higher for its own internal inferences. A throrough litterature review of their distinct advantages and implications in engineering practical conjugate models of intelligence across fields of cognitive science can be seen in (Lake *et al.*, 2017).

Apart from an abundant and diluted appreciation of the cybernetic legacy, it still remains the transcending aspect of postwar aesthetics where systemic loops would provoke interactions in a non-linear and potent modulation of information (A. Pickering, 2011; Halpern, 2014). Conjugating both models means that they should be interactive and mutually beneficial in overcoming each other limitations in order to exhibit evolution and mutual adaptation. That necessarily involves to rely on feedbacks to update information, that each ends should share an agency

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[36] See for example the synthetic descriptions of ideas about memory in 2.2.4.

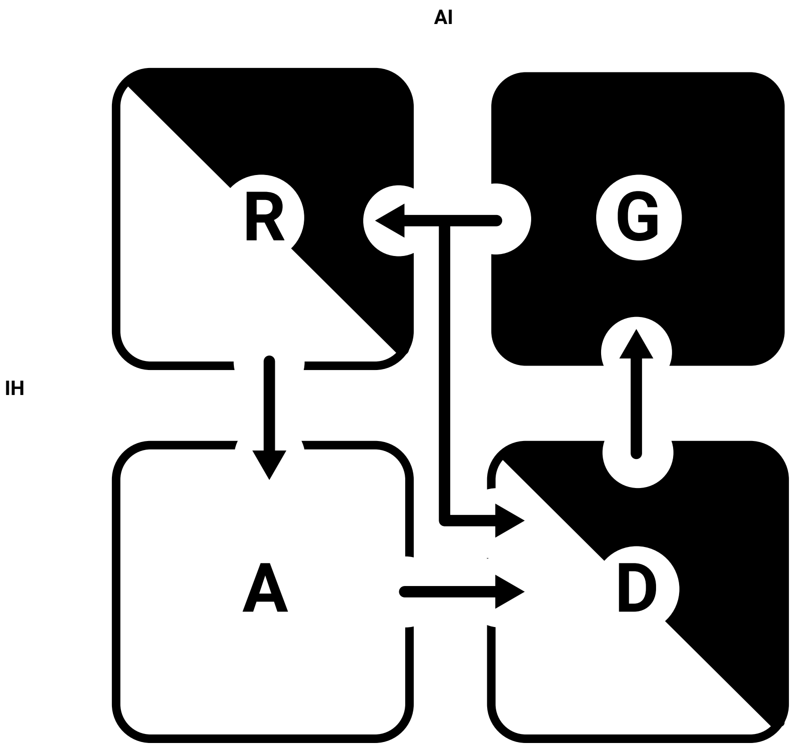

Figure 25: Schematisationof a circular coupling of both AI (right) and IH (left). The GRAD quadrium is described clockwise from generation (G), rendering (R), acquisition (A) and discrimination (D) and operating on sequential transformations of information. The loop is functionally closed but results in continuous derevolutions due to the intractable characteristics of IH. Challenges lie in each part of the quadrium in order to balance between explorative and exploitative modes. R and D are two opposites in the way they present information respectively to A and G, which in turn are assymetrically opposed in their encodings of discriminations and generations.

assymetrically to the task and in the way they operate. By assymetry, we mean that on the IH end, the intractability of its capacity to provide for discrimination implies an open loop and potential increase in dimensionality as a form of *heuristic graft* on the stochastic computational loop. Here we posit a general schemata to conjugate both IH and AI in the hypothesis that it might be applied to seek greater design variance in the modeling of architectural artefacts. As a quadrium, it articulates clockwise 4 distinct information and communication elements of: features *generation* (G), *scene rendering* (R), *conceptual acquisition* (A) and *beliefs discrimination* (D), compressed in the acronym GRAD (see Figure 25). On one side of IH, new information needs to be presented perceptually by the rendering of a scene ($R \longrightarrow A$). The acquisition (A) of new tokenized conceptual associations is transduced into neural potentials correlated as psychophysiological phenomena. This allows to encode and update the separation of learned beliefs by induction and to dynamically generalize a discriminator ($A \longrightarrow D$). Generated latent features are being discriminated by their relative distances to separated beliefs and the modulation of their numerical values ($D \longrightarrow G$). This involves both inputs from D and G for correlating prior features with their associated values coming from A in a double nested loop that accomodates for both temporalities of AI and IH. Iteratively, the composition of the rendered scene is being updated by inverse graphics from G for new presentations ($G \longrightarrow R$). R and D are both intermediate representations necessary to communicate from the domain of IH to the one of AI. ***This schemata should now become a ground hypothesis that future***

sought architectural modeling applications would inherit from greater variance by leveraging productivity, generativity and interactivity in a circular fashion where human discrimination and machine generation conjugate each other to navigate among information. In the following chapter, it will take more practical shapes in investigating the multidisciplinary research field of Brain-Computer Interfaces (BCI), where the synthesis center of psychophysiological events occur and can be interfaced with a computer in transmodal (analogue /digital) communication. The whole reason of going through such historical and theoretical venture beforehand is to identify which points are also architecturally relevant from a very basic core, on to its potentials. Retrospectively, the previous comments on the design research on interactivity of Frederick Kiesler comes back to mind[37]. Where the sought *corealism* resonates at the articulation of an objective generative model and a subjectively biased discriminative one.

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[37] See the last paragraph of 1.5.1

2.4.3 *Generative Design Without Grammar*

As noted by Manfredo Tafuri by the end of the 20th c. (Tafuri, 1980), *saussurean linguistics* permeated architectural discourses from the 1960's onward in an attempt to solve the problem of architectural meaning throughout analytic and structuralist methods heavily based on the linguistic analogy. Given what we previously unfolded, we now know that a cognitive turn have led to greater understanding and potentials about the idea of modeling that architectural discourses might have thought about. ***The crisis of meaning would never have been thought as a problem if meaning were to be thought as fleeting significance from the beginning***. *

In a critical period of the architectural idea of composition, Jean-Louis Nicolas Durand and Quatremère de Quincy emphasized the modern approach on the *architecture-as-language* thesis. While the former developed a grammar for instructional and infrastructural purposes (Lucan, 2009), the later did so to formalise ideological representations (Lavin, 1992). Giacomo Barozzi da Vignola may also be seen as an immediate precedent in that fashion, by establishing architectural codifications throughout distinctive shapes (Ware, 1994). More largely in a classic form, we could find such precedents in Vitruvius' intent to define rules in the Orders for the purpose of articulating parts, or Alberti's use of rhetorics for architectural descriptions (van Eck, 2000). Progressively, grammatical building blocks of the classical Orders became directly and metaphorically associated with semantic instances. Later on, it seemed to be tacitly understood as a necessary trade-off between articulating parts together with a desired variance of the times, and the efficient formalisation of pre-specific structures. By doing so, evading from the question on how to generate anything without the grasp of pre-specificity at all. One cannot help but notice a parallel trend with the abduction of reason in the modeling of intelligence and its functionalisation previously described from the 17th c. On[38]. Eventually, the syntactical legacy pervaded through the late 20th c. by establishing grammatical frameworks (Alexander *et al.*, 1977; Hillier and Hanson, 1984; Summerson, 1966; Alexander, 1979; W. J. Mitchell, 1990), prototypically computational but inherently formal and self-limited by becoming their own messages. For Charles Jencks, at the end of post-modern architecture and the 20 th c., architecture indeed possessed syntax, semantics and the capacity for metaphor(Jencks, 1977). Which retrospectively seems highly improbable given its incapacity to stabilise sufficient language-like features (Donougho, 1987; Langer, 1953; Clarke and Crossley, 2000; Forty, 2000; Scruton, 2013).

Rather, in every scope that regards architecture, meaning seemed to evade from syntactically inspired views and became as *diffuse* as modernism (Branzi, 2006). Regarding the role of a *building* in that aspect, and more generally here a *scene*, the features it might purport towards significance are rather denotative, in parts or wholes (Goodman, 1985b; S. Fisher, 2000) rather than semantically preloaded. It is in that sense that a minimised portion of the semiotic approach can be reappraised. Where objects may be seen as prompts for significance (Eco, 1986; Koenig, 1970) but should not involve further formalisation. It is under that light that we may say that architectural modeling is then best understood as a linguistic code (Mukařovský, 1977), but of the minimal type and not as semantic encoding. ***If architecture is to deal with articulations, its power must then reside in its vocabulary, not its syntax***. * And if grammar is to be involved, it should rather be involving the temporal dynamics that geometrical frameworks could not contain. Here, we recall the *architectural grammar* of Frank Lloyd Wright as indeed generative but with an organic base. Meaning that things refer organically to the same thing to form a whole aggregatively, in tradition of the *grammar of ornament* of Owen Jones (Jones, 1856; F. L. Wright, 1954). It also offered a strong *counterpoint* to the palladian plan regarding the idea of centrality. Where the humanist world of the centered Man was replaced by its modern pendant taken into perpetual flows and leaving compositional centers constantly occupied

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[38] See 1.4.

by other parts (Scully, 1960). Similarly to the way Andrea Palladio unfolded a vocabulary for visual architectonics(Hovestadt and Bühlmann, 2016), we should now follow by replacing the geometric center (of synthetic stability) by a harmonic one (of synthetic dynamism) in order to address the generative from a different domain.

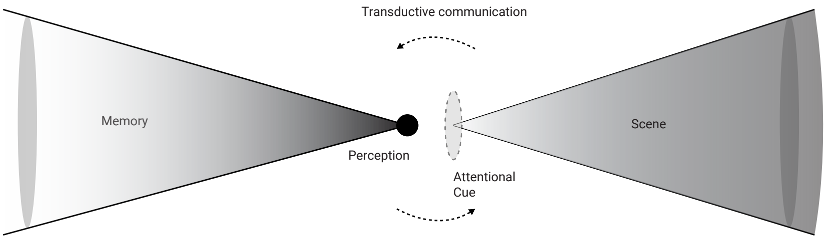

Figure 26: Schematisation of perception playing its transformative role in communicating significance. Minimal linguistics such as conceptual archetypes serve as lenticular cues to focus attention on iteratively presented compositional states of a scene on one side, and the associative schema of a concept from memory on the other.

In order to expand vocabulary beyond the framing of formal structures, the hierarchy should be inversed. Syntaxes should be tokenized and framed by vocabulary in order to bring more variance in emergent structures. Bluntly, words should come before phrases. This idea follows the path of the criticisms gathered along the past two chapters about formal analysis, and will allow to have a last look at cognitive linguistics and the turn it took towards morphodynamics in a similar fashion (Petitot, 2011). From a much larger project concerning the *naturalisation of the mind* during the cognitive turn, and for which we have previously observed a few of its actors, Jean Petitot synthesizes a specific point in the whole[39]. In his arguments for a *semiophysics* (Petitot, 1992), a similar critic regarding the mechanistic conception of algorithmic syntaxes occur through the design of their structural finitude. For Petitot, perception becomes essentially a work of differences. Discontinuous and marked by boundaries, it falls under the phenomena of *categorical perception*. As such, prototypical values are taken at the centroid of these perceived categories (Petitot, 1988). The difference between tokens of these categories and their prototypes generate a weight in memory depending on its amplitude. Inversely to a continuous perception scheme where every difference in a continuum is sensible to perception. What allowed for deeper articulations with the morphodynamics of the mind was to wonder how a perceptual system that is generally understood as ruled by continuous parameters in the mind can be discontinuous in states. The answer was in the critical phenomena, the *catastrophe* of René Thom's *morphodynamics* (Thom, 1974; Petitot, 1989). Once critical values are reached on a continuum and provoke the emergence of brutal changes of states or phases. This gave to the perceptual module a transformative capacity. The very basis of the collective project of naturalisation was that cognitive psychology and natural phenomenology are priors to natural language an can barely be asserted from formal analysis. What is perceptually relevant from the environment cannot be described in physical terms and renders geometry as an inadequate framing formalism. In brief, *physical lexicon and cognitive lexicon do not intersect* (Petitot, 2011) can be approached a minima as a form of lenticular cues, prompting for the recollection of particular concepts from memory in addition to the dynamic presentation of probabilistic grammars (see Figure 26).

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[39] See also the significant place his work took in the general discourse about computation in 2.1.3.

2.5 SUMMARY

This present chapter has been aggregating and synthesising ideas about modeling from the legacy of *apophatic* grounds and research precedents described in the previous introductory chapter. Organised in four main sections, the reflections starts from basic knowledge about scientific modeling, to venture across numerous research domains of CS and progressively draws towards architectural assertions.

To a wide extent, scientific modeling, as a thought experiment, forms a sort of analogue representation of collective beliefs and ideas about the world, its boundaries and its comprehension. We tried to antagonise two distinct ways to approach this way of thinking through the figure of the *gnomon* and the *demon* with the utility of, respectively, transcending boundaries and objectifying them. While their use is pervasive throughout the history of scientific thinking and ideas in general, the pattern they reveal is done so by probing the coherence and limits of human knowledge and capacities. Together, they establish prototypical ways to gather and emulate knowledge in a productive fashion. By doing so, they become both *experimental* and *instrumental* models for thinking and its articulations. Precisely, what architecture now greatly needs to reflect on both its intellectual legacy and its contemporary conditions. From the topic of architectural modeling, we then focus on the core idea of *architectonics* and the *archai*. Not only these were foundational in the development of architectural discourses about meaningful articulations, or *compositionality*, but they also expressed loose, yet potent, descriptions of what architecture ought to be in performing this compositional task. The main scope of the *architektōn* , as a form of peculiar intelligence, was both *syncritic* and *synthetic* in order to weave the fabric of the city. Which evidently involved certain models of thought enabling such thinking in a circular fashion. Physical artefacts involved in the complex organisation of the city revealed peculiar clues, barely present yet extremely significant, in how such sophisticated thinking is emphasised through the punctuation of magnitudes and the horoi. Local points and open horizons emerged as compositional objects and revealed the power of dealing with boundaries in dual modes.

Looking back into such potent legacy allows to perceive the beginning of new approaches regarding the contemporary topic of architectural modeling and the modalities of its encoding , or computation. Towards the end of the 20th c., the *invariance by variation* inherited from elementary geometry became a *variation by invariance* through the standardisation of digital codes. Yet throughout the project of *algebraisation of geometry* from the 16th c., the level of abstraction and structuration of the numerical approach proposed an unprecedented way to deal objectively with the idea of *novelty as a free creation of the mind*. A corollary to differential approaches, with its own way to deal with pre-specific structures in a productive fashion that computation holds as a potential yet not fully tapped on. Numerous confusions and falsely claimed stylistic formations in architectural modeling and thinking occurred while entangling both terms of *technique* and *technology* in a singular and cloudy description without taking into account the complementary positions they take in thinking abstractly about a concept and implementing ideas concretely. Eventually, codes became their own message. A better departure in the search of new potentials would be then to focus on the messaging technology rather than subsequent coding techniques and evade from traditional forms of architectural encoded depictions to tend to the very capacity of more abstract mechanisms of modeling. Translational perspectives about information and communication should support that path. But *coding* itself is not to be relinquished as a barely resulting effect. Rather, in its own potentials, it is a form of *expressionism* that transcends science and arts. One particularly strong aspect in that matter regards the transformative act of *modulation* that is inherent to the idea of expressing anything. In both domains, pictural modulations and algebraic convolutions can be seen analoguous to each other. Through the concurrent sophistication of such abstract and conceptual ideas, modulation techniques gained greater expressive potentials that concerned the modeling of intelligence at large, and provide for partial explanations of what happens to values in the mind and in numbers.

Apart from a widely accepted externalized approach about intelligence, its modeling and the interpretative shapes it took into architecture, an important body of work regarding the understanding of human cognition and the centrality of memory needs reappraising. For instance, asking the question on how *things-in-the-world* become *objects-in-the-mind* activates debates about perception, cognition and the primitive, prototypical, connections existing between things and thoughts as well as their internal representations. The way proto-object theories form a prior to representational content in the mind informs us on potent psychophysiological capacities to deal with the world and its uncertainties. In a traditional architectural thinking heavily loaded with a linguistics legacy, this also also allows to approach the temporal agencies of meaningful representations being formed from the dual perceptual/cognitive lens. *Proto-objects* are causally linked with particular concepts in order to make sense of the world and language lacks abstraction in order to allow for that linkage. Followingly, thought becomes prior to language and posits productive capacities that linguistics cannot frame. The synthetic and syncritic features of architectonics find a corollary in the internalized mind processes. However, since perceptual inputs cannot afford to be synoptic, particular focus must be attended in a timely fashion in order to remain productive. This is where language might find an adequate place to become operational in modulating attention and articulating the volatility of information. What role memory has to play in this capacity here is regarding its dynamics. There are extensive ways to observe the object of memory depending on the causal mechanisms of study. But the common pattern lies in locating generally early forms of *compositionality under attention* and the presence of emerging structured representations. In its earliest forms, memory is tightly linked with controlled attention in order to deal with fleeting sensory-conceptual representations. It represents a sort of *attentional joint* articulating both perceptual and cognitive contents.

Along its temporal dynamics, peculiar psyhophysiological phenomena can support these studies and inversely index the most probably salient stimulations which provoked changes in the dynamic relation. The general limitations of architecture to deal with change is intimately related to the fact that by being primarily anchored in space and graspable representations, it is cutting memory short of its productivity and remains a relation of the archival type. Brought out of time, *remembering* is separated from its counterpart that is *forgetting* and disallows architectural modeling to envision the past as an *open temporal horizon* and deal with the *volitionality* of its content. Recollection is a potent compositional process one should bring back on the table of architectural thinking for further architectonic potentials in a computational perspective. What memory allows as an active instrument of measure — that is measuring qualitative changes over time — is to deal with infinity. And by doing so, generates values in reference to specific concepts in the mind. Another aspect to enrich our approach about compositionality and its computational equivalence regards the visual mode and its associated technology in the way it may bring back to the eye potentials from the mind. The analogy here takes the shape of *inverse graphics* to generate compositionality from code that may enable sought expressivity. The world becomes a scene which structure is undefined, may be dynamic, and must be inferred through the discrimination of parts and scene relations in order to understand underlying causal structures. From local topological differences, structural description might emerge by *aggregation*. Not only this schematisation links both kinds of modelisation (ie. so called *artificial* and *natural*), but also brings a mechanism to computationally deal with uncertainty productively.

If composition can be seen as a work of the intellect, producing meaningful articulations from a scene is a feature of the mind. Some consequences of developing the reflection further fall back within the sophisticated vocabulary of architectural modeling. Where certain terms need revision and transposition with others more potent and descending from CS literature. Bringing back temporal dynamics into architectural compositions means that parts must, from now on, be considered as particular instances and therefore should be transposed with the idea of a *token*. By reticulation, the formation of modeled objects needs be reappraised as an *aggregative* process which integrates inferences. The rich debate about compositionality in architecture was always relying on the formalisation of particular syntaxes claiming generalizations of some sort. But the composite nature of architectural concerns always seemed to reveal their inadequacy to convey messages, instead of revealing that if there is an intractable component to composition itself that characterizes the synthesis of putting things together as a potent transformation, the problem is already the solution. Some precedent architectural reflections ought to be seen under that light such as *growth* and *organicity* regarding the temporal agency of architectural modeling.

Moreover, the way categories refer to an attributive and predicative function to things in the mind is very foreign to the way modernity interpreted categorization as analoguous to classification. Despite their differences in qualitative descriptions. One way the C/RTM would deal with categorization involves the psychosemantic framing of concepts in general. Concepts are psychological entities that impose on this process a pre-specificity that is not directly imbued to experience but plays a descending role in compositionality. Categorization becomes a similarity process involved in the linkage of perceptual content and concept formations, which incidentally looks like an aggregative process itself. This is in way, a circular model that mediates between thought and language and providing materials for our own sought designs. For the specific experience of architecture, we posit a model of natural communication, and where, involved messages are inevitably evolving and mutating throughout its course. And despite its volitionality, the mind does seem to struggle navigating through it. *Beliefs* in the mind have a causal /functional role in the propositional attitude they represent between an individual and the fluctuation of mental representations. Such unstable basic structures allow for navigation among thoughts and allow for observing their modulations. Beliefs update when new significant perceptual inputs occur and stimulate current conceptual schemata in the mind as a form of logical truth condition. A mechanism not only observed in humans but also studied in probability theories to encode decisions under uncertainty as a computational equivalent. One of the reason why vision was considered as a technology to study, is not only because of its extensive and transdisciplinary literature. It is also because it is widely considered as the most accurate mode of constructing internal models of the physical world. Evidently in concert with other ones playing their role in an embodied mind, but nevertheless the richest in features and synthetic transformations. Along its pathways, ICT models could be grafted and leverage its potentials. The intrinsically probabilistic nature of optical information itself suggests to articulate found vocabularies directly in the mind rather than their externalisation and use aforementioned psychosemantic phenomena and mechanisms to do so potently.

Back to the communication framework and its suggested dynamics, architecture should not be concerned by meaning but rather by *significance* as the holds better resilience to the volitionality of what it may purport. It is in that sense that architecture can hardly pursue any means to convey significance by isolating itself in the spatial domain and should rather be thought in terms of time and frequency, where significance actually operates, things take shapes and become objects. Extensively, a large part of architecture's potentials, its *virtuality*, takes place in an environment that is not already there in the physical world but in the mind and *yet-to-be* modeled. By reappaising the transitional period of early humanist renaissance with CS ideas about the importance of memory in dealing with significance, *durational aesthetics* emerge as a proper way to qualify the uncountable part of experiencing changes in the time and frequency domain and reinforce the idea of a *sensible* component to exploit in architecture, so dear to the *picturesque* of the 18th c. What is at stake for architectural modeling is to be able to leverage the intractable productive capacities of the human mind in a computational framework that might produce spatial artefacts of greater aesthetic potentials. With that concern pervading through this entire research, the conjugation of both approaches to model intelligence forms a dichotomy: AI and IH. It becomes a general schema to implement interactivity between both. Embedded in a circular fashion, a quadratic model named GRAD accounts for emulating and overcoming each other limitations and make the best of their characteristic capacities for *productivity* and *generativity*. As a technological perspective, these developments support a reactivation of the void left by the architectural crisis of meaning when asked if architecture had any role to play in making sense at all. What it allows is to transport the modeling of architectural objects to the free expression of combined vocabularies as a prior to emerging stable articulations expanding beyond formal structures. The prototypical role that language is left to play in that model remains minimal and serves the purpose of a focal lens under conditions of high *polysemy*.

As a whole, this chapter constitutes a prototypical theory on architectural modeling with neural potentials. What follows in the next chapter will relate efforts to develop empirical grounds for its implementation.

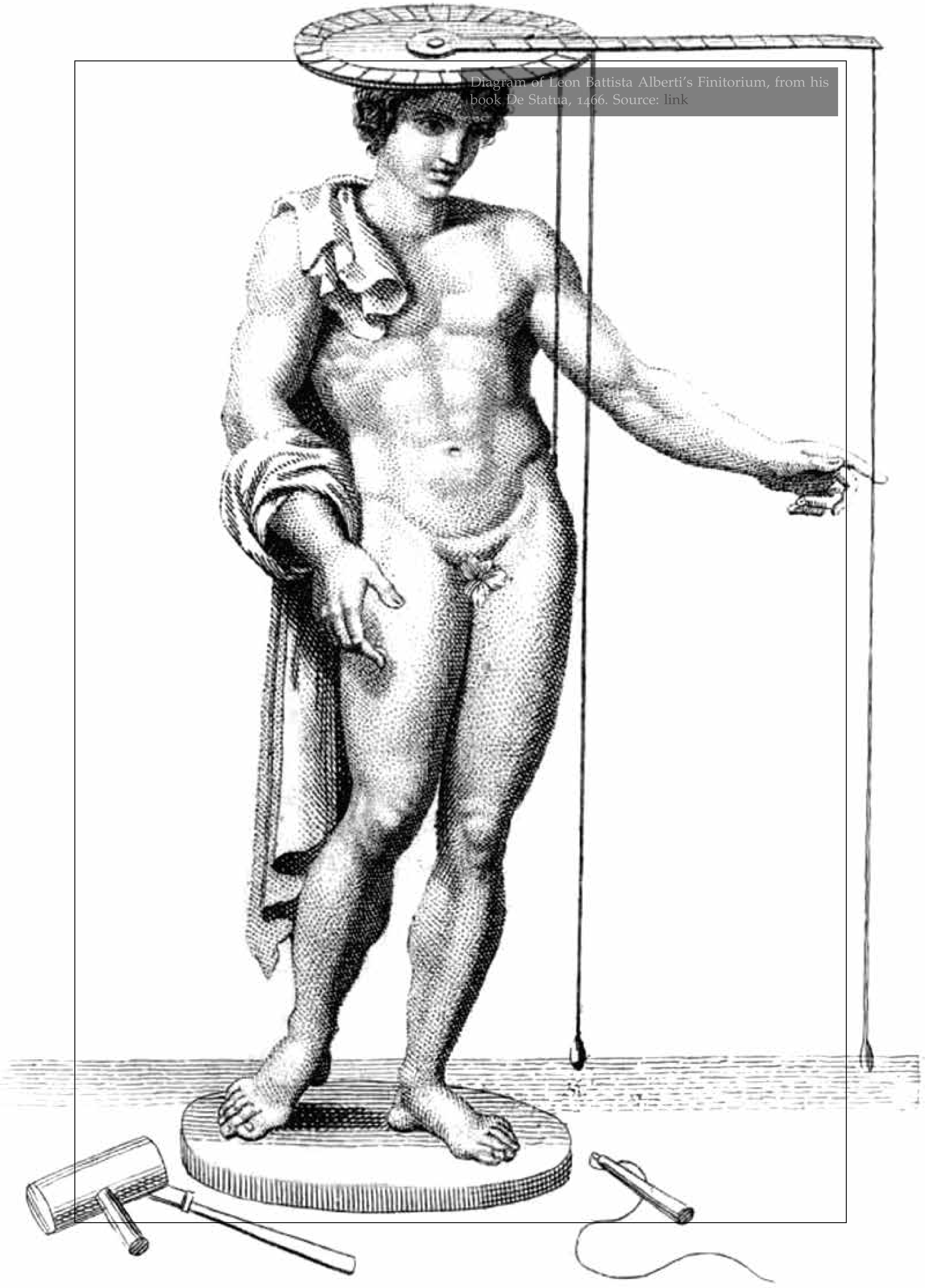
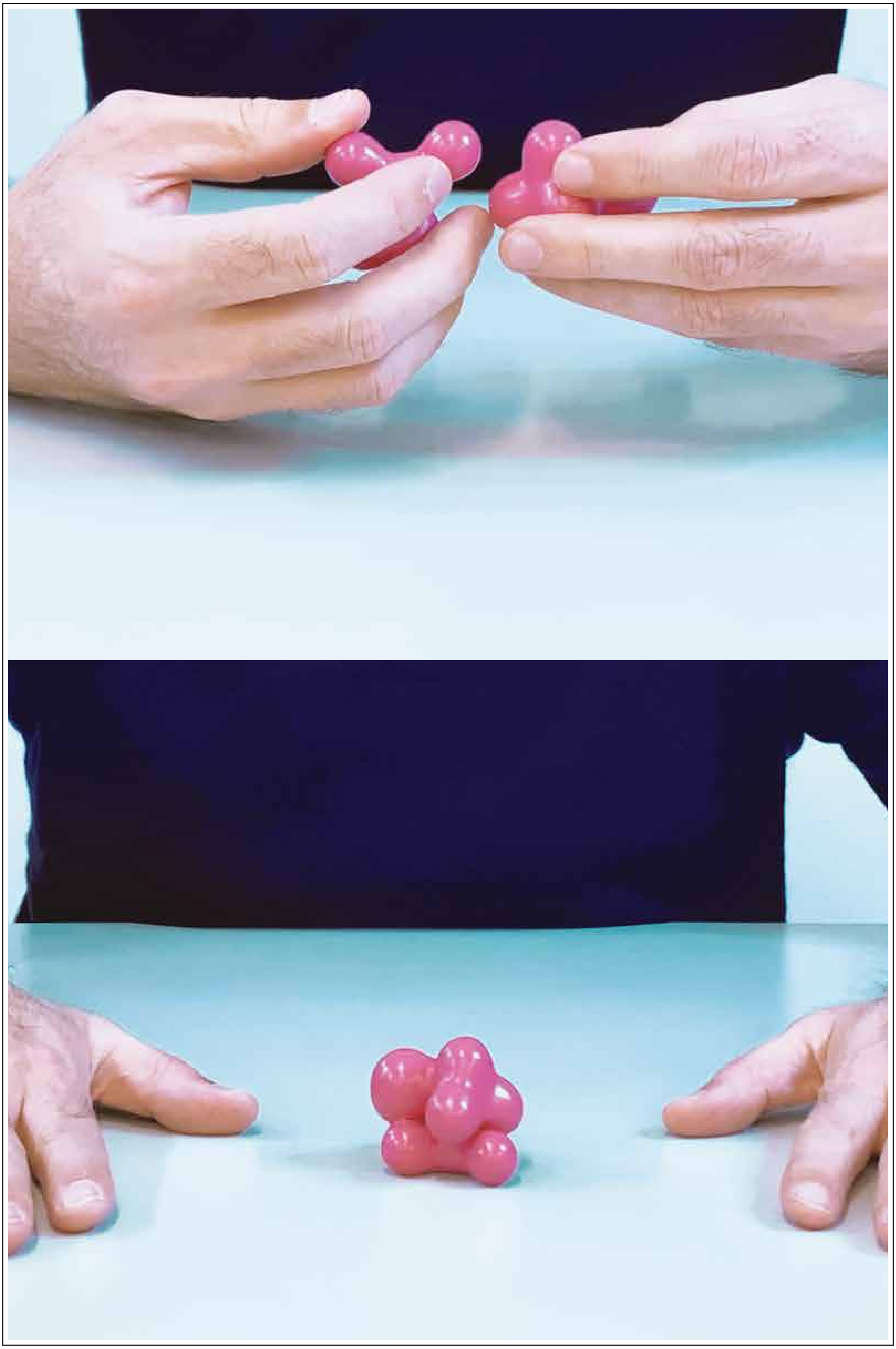


Diagram of Leon Battista Alberti's Finitorium, from his book De Statua, 1466. Source: link

EXPERIMENTS IN MODELING WITH NEURAL POTENTIALS 3

Next page: Composition sequence of two random physical parts. If putting parts together produces significance then how to grasp it?



3.1 COROLLARY REFERENCES

From the vast history (Myers, 2020; Grudin, 2016; Lotte, Nam, and Nijholt, 2018) and the state-of-the-art (Allison, Dunne, *et al.*, 2013; Nam, Nijholt, and Lotte, 2018; Stegman *et al.*, 2020) of employing Brain-Computer Interfaces (BCI) paradigms, and more largely *Human-Machine Interaction* (HMI) in the perspective of exploiting physiological synthetic responses to environmental stimuli in fields beyond clinical and assistive applications, it is important to identifiy what corollaries of the present research might enrich the field of investigation and comparison in specific goals and subdomains of applications. In fact, the historic phylum of interactions between the human intellect and the physical world could commonly be traced from the functionalisation of physical artifacts since the paleolithic apparition of hominids[1], or their intellectualisation for proof of conceptual boundaries about the world during Greek Antiquity[2]. From there, one could argue that all, if not every present ideas, in current implementations are not new but iterations of a handful fundamental ideas about human capacities to relate to the world such as ***probing, enhancing or recapacitating***. *

The main points of interest here are concerning the contemporary and technical implementations of such ideas, and therefore will drive focus from the second half of the 20th c. on. This starting period evidently coincides with several key events compound of the current dynamics in the popularisation of BCI applications. Among which, are worth mentioning the birth of personal computing, enabling everyone on the planet to potentially become a computer user without technical expertise in the late 70's (Campbell-Kelly *et al.*, 2014), the formalisation of cognitive science as a new discipline compound of subdomains of psychology, computer science, linguistic, and philosophy (Miller, 2003; Smelser and Baltes, 2001) and whose initial goal was to combine human factors with systemic scientific applications, the advent of electronic messaging[3] during the mid 70's and foreseeing what has now become social media and social computing transformed the popular perception of computers from mere functional and controllable tools to abstract communication machines enabling interactions between people through them (Schuler, 1994) while supporting human computations. From there, one can see the progress in engineering and expansion of BCI and related applications (see Figure 27) since the feature generalisation and control of *alpha* bands (Kamiya, 1973) and other neural activity for communication and control (Vidal, 1973) to the current period of advancements attempting moving beyond (Wolpaw, Birbaumer, *et al.*, 2002; Erp, Lotte, and Tangermann, 2012; Blankertz, Acqualagna, *et al.*, 2016). From the widely active research fields of applied BCI (Wolpaw and Wolpaw, 2012), corollary features and points of interest will be drawn for the present study and near-future research perspective. Prior to these corollary applications, a synthetic review of methods of reference will be laid out. Finally, it is to be noted that almost no major reference is drawn to the sibling research field formerly called *Brain-Machine Interface* (BMI) and which mainly intended to signify a separation between the use of invasive or non-invasive methods. While its goals are similar to the ones of BCI (Lebedev and Nicolelis, 2006, 2017), their techniques, levels of interaction and methods still remain different at the moment (Principe and McFarland, 2008) and cannot be realistically extrapolated to research and applications on humans in non-clinical states or *outside-of-the-lab* (OOTL).

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[1] See the description of paleolithic technologies in Link

[2] One can take as an example the thought experiment of the greek intellectual Archytas. While trying to outreach the edge of the cosmos by holding a staff at its limits and, by its remaining existence, proving its lack of known boundaries. See for example Heath, Sir Thomas Little. 1921. *A History of Greek Mathematics:* Cornell University Library.

[3] Link

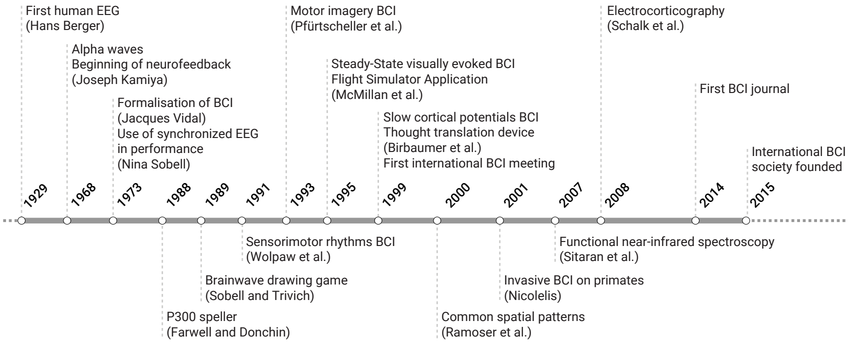

Figure 27: BCI general historical events across the 20th century from the formalisation of BCI to the generalisation and improvement of its methods and applications. Some discoveries related to invasive approaches are maintained here in the timeline due to their importance for the filed in general. Adapted from: Nam, Chang S., Anton Nijholt, and Fabien Lotte (eds) 2018. "Introduction: Evolution of Brain-Computer Interfaces." Brain-Computer Interfaces Handbook: Technological and Theoretical Advances, January, 1–8.

It is to be noted that the devised taxonomy is listing methods which can be either providing a specific distinct types of implementation or a combination of several of them. As there are no current perfect and universal recipe for BCI, their research and applications in the proposed review tends to map a framework to develop the research towards an applicative goal. They have been broadly reframed as a combination of methods of data ***acquisition***, BCI conditions enabling different forms of learning, or ***literacy***, the neural ***phenomena*** involved, their related ***signals*** processing and methods of ***measure*** for performance evaluations.

3.1.1 *Acquisition*

In the perspective of BCI implementations, two kinds of activity may be monitored through brain imaging: *electrophysiological*, generated by the electro-chemical transmission of information between neurons, and *hemodynamic*, generated by the release of glucose in the blood streams during neuron activations and measured through fluctuations of oxygen levels (oxy- and deoxy-hemoglobin concentrations). Their acquisition methods is generally rather dissociated first by their degree of invasiveness within the body.

A first distinction can already be operated from excluding invasive techniques and which find their main ground in clinical situations, justified for the purpose of rehabilitating humans. Current invasive acquisition methods can be categorised into two distinctive main techniques: *Electrocorticography* (ECoG), which consist in an intra-cranial electro-encephalographic recording (Leuthardt *et al.*, 2009; Schalk and Leuthardt, 2011), and *intracortical recordings* of neurons (INR) populations by micro-electrode arrays from *intracellular* to *Extracellular Action Potentials* (AP) and *Local Field Potentials* (LFP) generally widely used in BMI (Lebedev and Nicolelis, 2017; Hatsopoulos and Donoghue, 2009; Ryu and Shenoy, 2009; Waldert *et al.*, 2009). Among non-invasive brain imaging technologies, one can list *Electro-encaphalography* (EEG), *Magneto-encephalography* (MEG), *Positron Emission Tomography* (PET), *Single Photon Emission Computed Tomography* (SPECT), *functional Magnetic Resonance Imaging* (fMRI), *functional Near Infrared Spectroscopy* (fNIRS). While any of them have important distinctive advantages and caveats, only two can currently be addressed for non-clinical applications for reason of cost, size, safety and portability (see Figure 28). EEG (Swartz and Goldensohn, 1998; R. C. Smith, 2004) as the most popular and widespread (Hwang, Kim, *et al.*, 2013), fNIRS (Chance *et al.*, 1998; Coyle *et al.*, 2004; Naseer and Hong, 2015; Han *et al.*, 2015) as a promising one for passive measures of functional localisation, or even complementary of EEG (Tan and Nijholt, 2010) for accessing a larger and complementary range of potentials (Fazli *et al.*, 2012; Putze *et al.*, 2014; Khan, Hong, and Hong, 2014; Yin *et al.*, 2015; Shin, Kwon, and Im, 2018; Kwon, Shin, and Im, 2020).

The neurophysiological phenomenon *directly* recorded in scalp EEG originates from the dendrites of pyramidal neurons in the cortex (Cantor and Evans, 2013; Teplan, 2002) while an action potential is generated from the electro-chemical process firing between neurons (Nunez, 1995). Since EEG sensors, in the form of electrodes, are placed on the surface of the scalp (Teplan, 2002; Sharbrough *et al.*, 1991), their distance from firing neurons and the relative impedance from the skull and skin do not allow for high spatial accuracy but instead records local field potentials of slow amplitudes in micro-volts. The electrodes convert this ionic current flow from the scalp to an electron-based one going through external wiring to be amplified. The recorded activity is generally analysed in terms of power, amplitude and phase modulations and spans through several frequency bands which are generally defined fro common purpose as *delta* ($\delta :< 4Hz$), *theta* ($\theta : 4-7Hz$), *alpha* ($\alpha : 8-12Hz$), *beta* ($\beta : 13-30Hz$), and *gamma* ($\gamma :> 30Hz$) from low to high, respectively, and which reflect levels of activity in the brain (Lotte, Nam, and Nijholt, 2018). Despite its poor spatial resolution (0.1 to 2cm and above) rendering tasks inference difficult, as well as its poor *signal-to-noise ratio*, or SNR (Wolpaw, Birbaumer, *et al.*, 2002), EEG remains the main choice due to its relatively high temporal resolution (1 to 10ms) in combination with its low cost and manufacturing simplicity. Fundamentally different from electrical measurements of EEG, fNIRS is an *indirect* optical measurement of neural activity through a haemodynamic response (Lloyd-Fox, Blasi, and Elwell, 2010). Based on the principle of *neurovascular coupling*, or NVC, (Filosa, 2010), changes in this response correlates with neural activation (Coyle *et al.*, 2004). Sensors, in the form of light-emitting and photosensitive diodes called optodes, measure skin tissue property changes from its surface in the spectral range of near-infrared light (Jöbsis, 1977). Such wavelength frequency range allows for photons to access the superficial layers of the cerebral cortex and renders a more accurate spatial resolution (1 to 10 mm) but remains in a lower temporal resolution than EEG around 100ms and above (Kennan *et al.*, 2002). Similar placements than EEG may be used on the scalp either as complementary modes of the same source (ie. same locations, different modes of acquisition) or complementary locations and responses (ie. different locations, same or different responses).

In addition to potentially combining EEG and fNIRS, other modalities of measure such as *pupillometry*, or PPM, (Mathôt *et al.*, 2016) for covert attention, when BCI stimulations are vision-based, and which makes use of correlates of cognitive resources allocated to attending a task while remaining independent of a particular fixated location in the visual stimulus. A particularly interesting modality of acquisition regarding visual attention since it is independent from the eye gaze, does not presume spatial correlations in covert attention, and therefore might be able to provide a more synthetic reading of the visual environment. It is also worth mentioning the use of *Electro-myography* (EMG), *Electro-occulography* (EOG) and *Electro-cardiography* (ECG) to paliate to challenges and limitations of neurological signals (Scherer, Schloegl, *et al.*, 2007; Scherer, Müller-Putz, and Pfurtscheller, 2007; J. Ma *et al.*, 2015). Nevertheless, it remains important to consider the amount of information flowing in the interaction streams and the computational cost in maintaining that flow as well as practical implementations of any considered acquisition methods. Accordingly, many other external non-physiological signals may bring potent environmental information such as *eye tracking* or *gyroscopy* (Kim, Kim, and Jo, 2015; Li and Chung, 2015) for implementing switches or more explicit controllers under overt attention. Since neural activity constitutes the ground input paradigm for BCI, any combination of acquisition methods making use of only neural signals (eg. EEG + fNIRS) are considered as *homogeneous*. Whereas combination with other physiological and non-neurological signals are considered *heterogeneous* and *hybrid* (eg. EEG + EOG) (Choi *et al.*, 2017). Hybrid BCI is a common topic of research to address informational limitations and practicality (Pfurtscheller, Allison, *et al.*, 2010; Allison, Leeb, *et al.*, 2012).

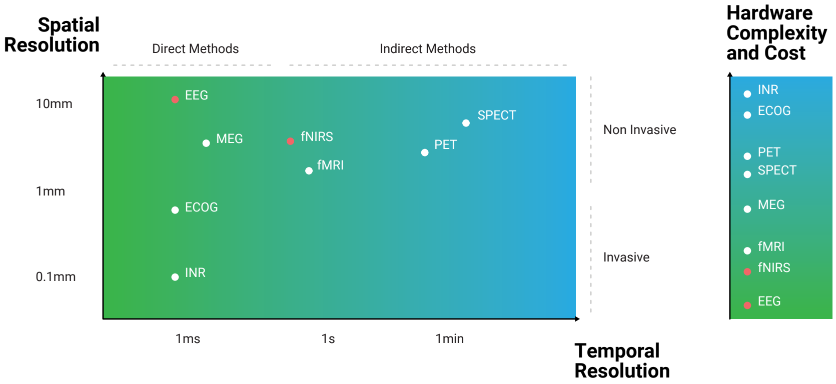

FIGURE 28: A synthetic 3 dimensional map of BCI acquisition principal methods (excluding non-neurological ones such as EOG, GSR,...), organised by spatial and temporal resolution as well as the hardware complexity (right axis). Adapted from: Nam, Chang S., Anton Nijholt, and Fabien Lotte, eds. 2018. "Brain–Computer Interfaces Handbook: Technological and Theoretical Advances". 1st Edition. Boca Raton: CRC Press. And : Nicolas-Alonso, Luis Fernando, and Jaime Gomez-Gil. 2012. "Brain Computer Interfaces, a Review." Sensors (Basel, Switzerland) 12 (2): 1211–79.

For practical reasons and in the perspective of research in CAAD applications, two levels of interests will be maintained in terms of acquisition methods: an immediate implementation of EEG methods for current experiments, and a longer term interest in the study and development of hybrid EEG-fNIRS for future improvements (Yin *et al.*, 2015; Kwon, Shin, and Im, 2020), in addition with the study of a heterogeneous complement of pupillometric data acquisition (Mathôt, 2018; Muto, Miyoshi, and Kaneko, 2020).

3.1.2 *Literacy*

Very much analogous to motor and cognitive skills learning, BCI has to be learnt by a user to produce and adapt significant neural phenomena as it establishes a non-innate communication channel between potentials and actions (Hiremath *et al.*, 2015). An individual has to repetitively succeed in communicating with a computer thereby. It is therefore common to relate to the term of BCI *literacy*, in the stable acquisition of such communication *skills*, or *illiteracy* should it be experienced with difficulties (Dornhege *et al.*, 2007; Vidaurre and Blankertz, 2010). However this task does not have to be entirely assumed from a human perspective and should be adequately shared with computer-based ones. The concept of literacy in BCI literature has been generally criticised for its implications in negatively describing a failure to learn a task as a form of illiteracy instead of assessing encountered problematic physiological and functional conditions as a challenge to answer adequately eg. (M. Thompson, 2019). The task, nevertheless, needs to be assessed in a dual fashion. The term is referred hereafter in search of a virtuous cycle instead of antagonising this issue. In order to achieve such literacy from a human user's perspective, several non-exclusive approaches currently exist. We will gather them here under the term of *literacy methods* in order to provide a clear differentiation with *learning methods* described hereafter and specifically regarding neural decoding. It is our understanding that literacy methods can then be broadly divided between different types of main conditions: *interaction*, *responses*, *stimuli*, *presentations* (see Figure 29) and two different types of adaptivity: *subject-adaptation*, *machine adaptation*.

Different levels of interaction in produced neural responses may be categorised into three main levels of involvements from a user's neural activity: *active*, *reactive* and *passive*. While an *active BCI* would involve a user to consciously modulate brain activity to produce a neural response independently from external sources of stimulation (given that a neurofeedback would be considered as a stimulation), a *reactive BCI* would produce an external stimuli for a user to indirectly modulate neural activity, whereas a *passive BCI* (T. Zander *et al.*, 2007; Cutrell and Tan, 2008) would make use of spontaneous and involuntary user activity, neither subject to stimuli nor conscious modulation, to produce an interaction (Rötting *et al.*, 2009; Brouwer, van Erp, *et al.*, 2013; Mühl *et al.*, 2014). These distinctions also imply certain preconditions in the temporality and modes of expected responses. Interactions which are reactive and task-relevant are said to be *cue-based* and considered *synchronous*, as they require a clear synchronisation in time/frequency between a recorded neural activity and produced elicitations from the computer (Nicolas-Alonso and Gomez-Gil, 2012; M.-H. Lee *et al.*, 2015; Soekadar, Witkowski, Vitiello, *et al.*, 2015). Active and passive interactions may be implemented under both *synchronous* and *asynchronous* conditions, since they are not tied in synchrony with an eliciting event and can be *self-paced*. As *asynchronous* BCI interact with self-paced neural responses, voluntary or not, and independently from elicitations (Sg and Ge, 2000; Pfurtscheller, Solis-Escalante, *et al.*, 2010; Diez *et al.*, 2015). Any combination of modes of interaction and synchrony are also possible and may enhance the design of the interface (T. O. Zander *et al.*, 2010; Zander and Kothe, 2011). While a synchronous mode could focus on learning from the task at hand, an asynchronous one could assist in adapting its ergonomics. Both can also be combined in a two-stage fashion and where a synchronous mode could be used for the training of a discriminatory classifier, and an asynchronous one for task attendance (Pfurtscheller, Solis-Escalante, *et al.*, 2010; Diez *et al.*, 2015). Other terminologies in relation to the causality between a muscle movement and a produced signal such as *dependent/independent* BCI will only be briefly mentioned here since they would only bring justified distinctions under rehabilitating scenarios (Wolpaw, Millán, and Ramsey, 2020).

Under these conditions, two main operative strategies may be applied to the production of neural signals: *operant conditioning* and *selective attention*. Such a behavioural method as *Operant Conditioning* aims at *covert control* of a task by providing feedback and assumes a form of implicit learning (Frensch and Rünger, 2016; Kaplan *et al.*, 2005). It diverges from *Respondent Conditioning* (also referred as *Classical Conditioning*, or *Pavlovian*), which assumes an *overt control* of the task (Ruf *et al.*, 2013; Meng *et al.*, 2018). Operant conditioning seeks to provoke adaptation from neural plasticity, in a *Hebbian* perspective, for an improved mapping of produced neural activity into task's procedures (Gluck, Mercado, and Myers, 2007). Operant conditioning constraints signals to be independent from external stimulus and modulated either by movement-related efforts, mental speech memory tasks, or any other kind of cognitive efforts and motor imagery related processes. *Selective Attention*, on the contrary, implies that signals are evoked by an external stimuli (Kramer, Wickens, and Donchin, 1985). Therefore cascading conditions may be created since selective attention would necessarily be used in a synchronous and reactive mode of operation, while operant conditioning would be asynchronous and either passive or active depending on the user's intentionality of modulating a signal.

To these preconditions of learning, a certain degree of *feedback and stimulation* is involved. Feedbacks may be concerning the online performances of a user while executing a task, or its results. While performance feedbacks can be continuous, or frequent, result feedbacks are discrete and generally formalise the success or failure of the task. They can be sensory, in their less invasive forms, such as visual (Sellers and Donchin, 2006), auditory (Nijboer *et al.*, 2008), tactile (Brouwer and Van Erp, 2010), multimodal/hybrid combinations (Hinterberger *et al.*, 2004; Barbero and Grosse-Wentrup, 2010), or somatosensory through electrical stimulations of nerve pathways (Romo *et al.*, 2000; Miller and Weber, 2011). While feedbacks may help to infer on a task, stimulations are aimed at accelerating its learning (Soekadar, Witkowski, Birbaumer, *et al.*, 2015) by assuming a form of *associative learning*. Electromagnetic stimulations such as *transcranial direct current stimulation* (tDCS), or *optogenetics* (yet not fully mature) are two promising forms of cortical stimulations to induce neural patterns (Ang, Guan, *et al.*, 2012; Lima and Miesenböck, 2005; Pashaie *et al.*, 2014). However, while stimulations are not realistically justified in any other application than the rehabilitation of specific tasks (eg. motor control of specific limbs), feedbacks may very well get in the way of the task itself by generating distractions, if the application is not specifically meant at the sole modulation of the neural signal (eg. meditation). It is therefore a better assumption to tend to fuse feedbacks and task presentations together either in their presentation modalities (time and frequency), or sensory ones in order to minimise their negative impact. Feedbacks may also be considered as the direct output of the end process generated in the loop, and generally define a *closed-loop* in an interaction. When it is not the case and a mediated response is devised from the output or not, the interaction is considered to be in an *open-loop* (Wessberg *et al.*, 2000).

Presentation conditions concern only the modalities of stimuli, tasks, or their fused compound. Depending on other conditions aforementioned regarding levels of interaction, responses and stimuli, conditions of presentation may greatly vary. Not to mention acquisition, and sensory or somatosensory modalities which might tighten even more the framing of presentation conditions. From a neuropsychology perspective, presentations may be of two kinds : *discrete* or *continuous*. While the former would involve at least one to many occurrences in time/frequency domains to clearly segment them and correlate with co-occurring signals (Farwell and Donchin, 1988), the later would present stimuli with no domain dependency (Neuper, Schlögl, and Pfurtscheller, 1999). In that aspect, stimulus types such as music or video may be presented in one presentation modality or the other (a sequence of frames or a continuous stream) depending of their domain rates and parameters involved. When fused with feedbacks, discrete presentations may be re-sampled and continuous ones modulated. Such presentations are generally called *Rapid Serial* and characterized by a somato/sensory type (Spence and Witkowski, 2013; Franco *et al.*, 2015; Takeuchi *et al.*, 2018), when discrete, and are aimed at the elicitation of neural responses. Tightly linked with *Signal Detection Theory* (Green and Swets, 1966), It is mainly used for discrimination tasks and where signal correlations with presented stimuli fall under one of four distinct classes : True Positives (ie. a correct hit), True Negatives (ie. a correct reject), False Positives (ie. a wrong hit) and False Negatives (ie. a wrong reject). On the other hand, continuous presentations mostly concern *Domain Modulation* (Wu and Zhai, 2013; N. Müller *et al.*, 2009) to aim at a paired modulation of cognitive states. They are generally implemented with *Diffusion Boundary Models* (Ratcliff, 1978; Ratcliff *et al.*, 2016) , or *State-Space Models* (Kalman, 1960; Bonnen *et al.*, 2015) for evidence accumulation over time of behavioural estimates (Huk, Bonnen, and He, 2018). Discrete conditions take a significant role under specific interaction modes and even more significantly in evoking responses through selective attention (Pashler, 1998; Kutas, Kiang, and Sweeney, 2012). Among the plethora of discrete presentations types aiming at evoking responses, one may list various paradigms such as *oddball* (Donchin, 1981b) for mismatch negativity and sensory discrimination, *n-back* (Kirchner, 1958) for memory retrieval, *go-nogo* (Friedman, Simson, *et al.*, 1975) for readiness and chronometry, semantic anomaly and priming (Kutas and Hillyard, 1980).

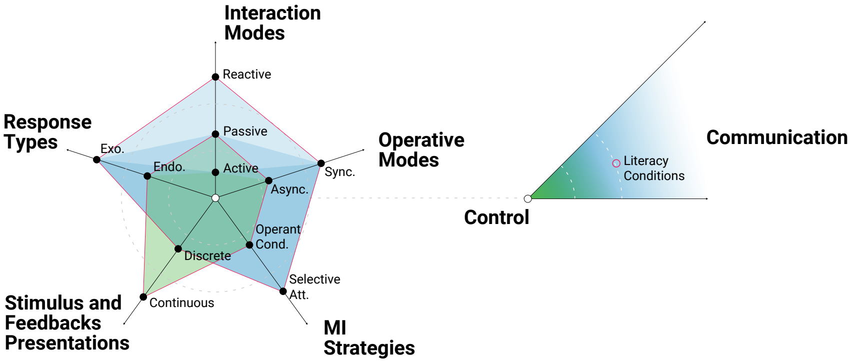

FIGURE 29: Graph generalisation of BCI conditions for literacy methods. Left - Organised through 5 main condition axes: modes of interaction, modes of operation (synchronous, asynchronous) — ordering all conditions in two principal domains (blue, green) —, mental imagery strategies (operant conditioning, selective attention), stimulus and feedbacks presentations (discrete, continuous), and neural response types (endogenous, exogenous). Outlined in pink are two complementary domains of interest. Right - The axes direction denote the aim of the task to be accomplished under these conditions, ranging from control to communication. Hybrid conditions may be approached when the aim is at the intersection of several domains.

Co-adaptive methods posit a periodic modification of an encoder (the human brain) and a neural decoder to progressively adapt to each other through neural plasticity and automatic calibration (Taylor, Tillery, and Schwartz, 2002). The adaptation can either take turn in which end adapts to the other, incrementally adapt a decoder at each session, or retrain a new one every time (W. Wang *et al.*, 2013; Ganguly and Carmena, 2009). Since BCI essentially establishes a communication and control loop between two models of intelligence, It is appropriate to approach co-adaptive methods as a *two learners* scenario. Where *subject learning* considers methods from a user's perspective, and *machine learning* considers the variability of signals. An initial mathematical model of the two-learners problem currently exists (see Figure 30) to help in the progress of that formalisation (J. S. Müller *et al.*, 2017).

Regarding adaptive subject learning, Behavioural methods such as *flow and shape* aim to provide adaptive support in the learning difficulty and specificity of a task or a feedback. It borrows from the pyschology theory of *flow* (Csikszentmihalyi, 1990) in the scope of maintaining the threshold of learning away from anxiety or boredom produced by the subjective difficulty of a task. *Shaping* is a related theory of reinforcement (Skinner and Ferster, 1957) which aims at progressively refining the task to greater complexity, precisions and levels of control (Gluck, Mercado, and Myers, 2007). Applied to BCI in the form of assistive methods, flow and shape can be combined, or used independently in either an *active* (participating actively in the execution of the task) or *passive* fashion (providing constraints decreasing the difficulty to execute the task) (W. Wang *et al.*, 2013; Velliste *et al.*, 2008), and that could complement the previously mentioned definitions of active/passive/reactive BCI. Such generalisations may concern involved parameters (eg. pace, stimuli speed/frequency, resting period, . . .) of feedbacks or stimulations if applicable. Maintaining progress in the learning rate constitutes a principal challenge for such methods, which need to apply adaptive training schedules (Y. Zhang *et al.*, 2012). Based on main instructional design prescriptions (Shute, 2008; Lotte, Larrue, and Mühl, 2013), feedback and tasks can be better fit to learning if they also adopt techniques close to game design (eg. environments designed for flows of engagement), implement a progressive complexity (McFarland, Sarnacki, and Wolpaw, 2010), a variability of training tasks, individual profiling, instructive and compelling feedbacks about the current progress achieved between current performances and expected ones, as well as prespecific cues of expected results of prior successful ones as a way to inform on task expectations (Lotte, Larrue, and Mühl, 2013; Jeunet, 2016). Adaptive individualisations methods may also help by using subject-independent classifiers at the beginning to progressively fit to a particular user (Vidaurre, Sannelli, *et al.*, 2011). It remains uncertain to what extent adaptive changes of the BCI conditions and parameters may infer on subject learning and overall performances and its metrics must be decoupled from the machine learning part (Lotte and Jeunet, 2017). Adaptive subject learning remains a fairly recent subfield of research to broaden BCI literacy and application potentials. Recent insights suggest to base such metrics on longitudinal (long-term) evaluations of improved separability of manifolds within decoded signal features (Perdikis and Millan, 2020).

During the past 10 years (ie. from ca. 2010), it appears that the question of classification and adaptation progressed rapidly towards a merged endeavour (Schlögl, Vidaurre, and Müller, 2010; Lotte, Bougrain, Cichocki, *et al.*, 2018). To the point where *zero-calibration* classifiers have become a targeted standard. While it still remains an active subject, the main research on adaption for a given classifier, may now be seen as comprised of two, non-exclusive (Congedo and Sherlin, 2011), approaches: *auto-adaptive calibration* and *data-space adaptation* (ie. *transfer learning*). While both approaches are concerned with adapting to the variability of a signal and or its scarcity, *auto calibration* will infer on a classifier's conditions to try to match expected outputs (Schlögl, Vidaurre, and Müller, 2010) whereas *data-space adaptations* would try to infer on the domain of learned outputs to fit new ones (Pan and Yang, 2010). Classically, adaptive classifiers see their parameters (or weights) attributed to each feature learned to be re-valued over time when new data is coming. However, this update may be viewed through either directly modifying the weights through calibration, or by modifying the data domain before giving it for training. End-user calibration still plays an important role in BCI research. But as it tends to becoming a decreasing issue in more recent machine learning methods applied to BCI (Schlögl, Vidaurre, and Müller, 2010; Lotte, Bougrain, Cichocki, *et al.*, 2018), one may still refer to several noticeable group of methods: *ensembles* or other mixtures of estimators (Soria-Frisch, 2013; Verhoeven *et al.*, 2017), re-computing a general *data mean* (Vidaurre, Kawanabe, *et al.*, 2011) or *covariance matrices* (Vidaurre, Schlogl, Cabeza, *et al.*, 2006; Zanini *et al.*, 2018; Hosseini, Bavafa, and Shalchyan, 2019). General indices may also be computed over a large part of the provided data to infer on the calibration of a classification pipeline. For example, *reward signals* such as

Error-related Potentials, or ErrP (Falkenstein, Hohnsbein, *et al.*, 1991; Chavarriaga, Sobolewski, and Millán, 2014) may be used for adjusting labels or weights under reactive and synchronous conditions (Zeyl *et al.*, 2016). Dedicated classification pipelines may also be used for evaluating cognitive and affective states under asynchronous conditions (Appriou, Cichocki, and Lotte, 2020) in parallel, or concurrently, to synchronous ones. Transfer learning methods become particularly useful to extend the robustness and generalisation of a learning pipeline across modes and domains. Two main forms may be noted for BCI general interests : *inductive* and *transductive* learning (Lotte, Bougrain, Cichocki, *et al.*, 2018; Azab *et al.*, 2018). *Inductive transfer learning* concerns the transfer of known classification, from a source data to a new target one, when both source and target feature domains are similar but task ones are different. They are generally characterised by different modes of acquisition (eg. visual and auditory) for similar neural phenomena (eg. P300) therefore conditioning similar feature domains but different task domains (Lotte, Bougrain, Cichocki, *et al.*, 2018; Azab *et al.*, 2018; Coelho Rodrigues, Congedo, and Jutten, 2020). In non-clinical conditions, induction would be also useful for enhancing the detection of specific physiological phenomena with hybrid BCI (eg. EEG + fNIRS). *Transductive transfer learning* is, in contrast, concerned when the feature domains differ but the task ones are similar. It generally correspond to BCI conditions where subject and/or sessions are different but modes are similar (Lotte, Bougrain, Cichocki, *et al.*, 2018; Azab *et al.*, 2018; Coelho Rodrigues, Jutten, and Congedo, 2018), and help to generalise task learning across subject/sessions domains when other BCI conditions are fixed (eg. A repeated EEG acquisition of a visual P300 speller for several users). The plethora of corresponding methods consist of establishing a common vector for transfer across domain. Should they be *instance-based*, *feature-based*, *classifier-based* or *relational-based* (Azab *et al.*, 2018). Once BCI conditions have been established, transfer learning methods should come along with identified classification pipelines to select an adequate method since it might affect the capacity to deal with datasets variability and biases (Lotte, Bougrain, Cichocki, *et al.*, 2018). Emerging comprehensive and generic adaptive frameworks based on *active inference* (Mladenović, Joffily, *et al.*, 2017; Mladenovic *et al.*, 2020) should help to support co-adaptive implementations. It is to be noted that deep learning approaches may also become competitive approaches once larger and consistent datasets would become available (Schirrmeister *et al.*, 2017). A subsidiary approach, concurrently to classic simulations, can in the meantime consist in augmenting datasets generatively (Abdelfattah, Abdelrahman, and Wang, 2018; Aznan *et al.*, 2019) and can also serve for the purpose of transfer learning studies (Kalunga, Chevallier, and Barthélemy, 2015; Gu *et al.*, 2020).

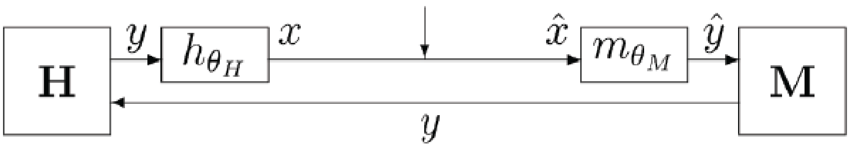

Figure 30: A symbolic representation of the noisy communication model between a human (H) and a machine (M). Source: Müller, Jan Saputra, Carmen Vidaurre, Martijn Schreuder, Frank C. Meinecke, Paul von Bünau, and Klaus-Robert Müller. 2017. "A Mathematical Model for the Two-Learners Problem." Journal of Neural Engineering 14 (3): 036005.

3.1.3 *Phenomena*

Established preconditions to acquiring and learning lead to two different kinds of expected phenomena in neural responses: *exogenous* (or evoked responses), and *endogenous* (Tan and Nijholt, 2010). Exogenous responses are signals produced while attending to a particular external stimulus under selective attention and are generally characterised by either transient or steady-state evoked potentials. Endogenous responses are self-paced and can be conditioned under cognitive efforts and biofeedback or totally independent from any external stimulation. They are broadly characterised under operant conditioning (see Figure 31).

Two main types of *endogenous responses* can be identified under operant conditioning: *sensorimotor rhythms* (SMR) for motor imagery, and *slow cortical potentials* (SCP) for diverse cognitive efforts under attention. Endogenous responses, by definition, do not need direct elicitations to be produced and are mostly found within passive or active interactions. They also must necessarily be asynchronous and therefore are found during operant conditioning, with continuous or no feedback at all. All three types are transient and require substantial training to exhibit voluntary control.

SMR are related mainly to motor functions (Nicolas-Alonso and Gomez-Gil, 2012; Pfurtscheller and Neuper, 2001). They are usually characterised in amplitude or power variations by either a decrease or increase in low frequency of the *alpha* (ca. 7–13Hz) and *beta* (ca. 13–30Hz) bands (Pfurtscheller and Lopes da Silva, 1999) in sensory motor cortices. Such increase is commonly labelled an *event-related synchonization* (ERS) whereas a decrease is an *event-related desynchronisation* (ERD). ERD/ERS may be produced voluntarily or not, from diverse *motor imagery* tasks (Pfurtscheller and Neuper, 2001) without necessarily any actual movement (Jeannerod, 1995). SMR are generally used in overt control tasks (Wolpaw, McFarland, and Vaughan, 2000; Pfurtscheller, Neuper, Muller, *et al.*, 2003; Blankertz, Losch, *et al.*, 2008; Blankertz, Sannelli, *et al.*, 2010) either in synchronous or asynchronous modes It is found that the amount of training necessary remains quite substantial from the subject side (Lotte, Nam, and Nijholt, 2018) and tasks complexity may only reach a maximum of 3–4 instructions at a time to maintain performances (Kronegg *et al.*, 2007). Continuous presentations of real time neurofeedback is generally preferable to enable the training of better ERD/ERS modulations (Hwang, Kwon, and Im, 2009). They can be detected with EEG and MEG recordings (Pfurtscheller and Lopes da Silva, 1999) and fNIRS (Fazli *et al.*, 2012) around the sensorimotor cortex but remain relevant to a wide range of applications (Yuan and He, 2014).

SCP are characterized by relatively slow voltage shifts across the cortex, typically from the frontal to vertex regions for maximum amplitudes found in EEG (Birbaumer *et al.*, 1990), and lasting from several hundred milliseconds to a few seconds and below 1Hz (Birbaumer *et al.*, 1990). These potentials correlate with fluctuations in cortical activity (Strehl *et al.*, 2014) and support the analysis of cognitive efforts. While negative potentials suggest an increased activity (eg. a movement), a positive one would correlate with a decrease (eg. a period of rest) (Rockstroh, 1989). A characteristic negative SCP called the *contingent negative variation* (CNV) is correlated with anticipatory attention, motivation, and motor preparations (Walter *et al.*, 1964; Fan *et al.*, 2007). Like SMR, SCP can be produced voluntarily or not through substantial training (Hinterberger *et al.*, 2004) with continuous feedback or not (Kaiser *et al.*, 2001) but remain highly variable among users. Given their relatively low speed of detection, high demand of training, and low information transfer rate, such endogenous responses keep the advantage of being self-paced but tedious to maintain control. In non-clinical states they find their main interest in assessing cognitive states and indexing mental resources such as attention of ongoing mental tasks. By this, they become important components of study for co-adaptive methods (Krol, Andreessen, and Zander, 2018).

Exogenous responses may be dissociated by either a *steady-state* or a *transient* one. But since all are evoked responses, the majority of BCI conditions make use of selective attention with synchronous and reactive methods (Nicolas-Alonso and Gomez-Gil, 2012). Within transient responses two types of *evoked potentials* (EP) are generally found in BCI designs: *motion-onset evoked potentials* (mEP), and *event-related potentials* (ERP). While steady-state ones are subdivided by their sensing mode as *steady-state potentials* (SSEP). Since synchronicity is an intrinsic property of exogenous responses, we will mention their signal characteristics only in EEG.

Since their first use in BCI (F. Guo *et al.*, 2008), mEP have been used in the visual field (mVEP) to counter the problem of visual fatigue or repetition blindness caused by more discrete kinds of elicitation. They are elicited by the motion of visual objects and are not sensitive to contrast or luminance factors (Kuba and Kubova, 1992). Related to attention mechanisms of motion perception (Kuba, Kubová, *et al.*, 2007), their amplitudes can be modulated thereby (Torriente *et al.*, 1999). They can be recorded around the temporal parietal and occipital regions of the cortex (Kuba, Kubová, *et al.*, 2007). It is also known that mVEP have a low inter-subject variability (F. Guo *et al.*, 2008) and constitute robust phenomena for better generalised BCI (T. Ma *et al.*, 2017). mVEP are typically exhibiting two variants in EEG amplitudes post-motion onset stimuli, depending on the interval between stimuli, and composed of three positive or negative peaks (Kuba, Kubová, *et al.*, 2007) labelled P1 (circa. 130ms), N2 (160–200ms), P2 (circa. 240ms). As many of these peaks can be shared with other attention related phenomena, motion based elicitations are sometimes combined with others to amplify peak amplitudes of other related responses (Martens *et al.*, 2009; Jin *et al.*, 2012). From this point, motion elicitation can be envisioned into other kind of elicitations and where mVEP may constitute an index of attention seeking to augment amplitudes of other attention-based phenomena (Choi *et al.*, 2017).

Event-related potentials are a set of standard and robust electrophysiological potentials, abbreviated as ERP, reflecting *higher-order* brain processing invoked in relation to mentations such as memory, expectation, attention, or changes in the mental state, rather than simply evoked by the physical impingement of external stimuli (Luck, 2014). ERP waveforms can be comprised of many diverse, and not necessarily consecutive, time-locked components characterised approximately within the first second after stimulus. It generally supports the timely epoching of evoked mental processes towards higher order of cognition. The first appearing component onset stimulus is a deflection labelled C1 (circa. 50–100ms) and generated from the the primary visual cortex (Clark and Hillyard, 1996). Following are negative N1 and positive P1 deflections as information is processed through perceptual analysis in the visual system and denote early discrimination (Vogel and Luck, 2000). Among which, a waveform correlated with covert attention in peripheral targets labelled N2pc (Luck and Hillyard, 1994). It is a negative deflection occuring circa. 200–300ms about the posterior contralateral region of the cortex and may serve to indicate the general direction of attention for visual search (Eimer, 1996). A prior negative deflection found maximal over the occipito-temporal region of the cortex, the N170, is argued to reflect pre-categorical structural encoding of faces (Eimer, 2000). A similarly studied potential at the vertex region of the brain (ca. 150ms) is also the *vertex positive potential* (VPP). The well known *P3 complex* (Polich, 2011), N2 and P3 followed by a slow wave (Kutas, Kiang, and Sweeney, 2012), are studied for the categorisation of a stimulus, generally in the visual field, object recognition memory encoding, and sensory discrimination (Woodman, 2010). A similarly studied ERP studied in the auditory field is the *mismatch negativity* (MMN), a negative deflection occurring in the fronto-central region ca. 100–300ms onset stimulus and for about 150ms (Kutas, Kiang, and Sweeney, 2012). Later responses are found to relate to motor preparation, such as the *lateralised-readiness potential* (LRP), an increasing negativity occuring between 500–1000ms onset stimulus and before the onset of an actual movement (Deecke, Scheid, and Kornhuber, 1969). More refined dicriminatory processes in recognition memory such as face familiarity can be observed with ERP in the frontal region such as the FN400, FP600 (Touryan *et al.*, 2011). ERP may also extend after an exhibited behavioural response to a stimulus for evaluation of performance errors. The *error-related negativity* and *positivity* (ERN, Ne/Pe) respectively frontocentral negative maximum peaks and subsequent positive maximum ones at the centro-parietal region (Falkenstein, Hoormann, *et al.*, 2000). Among the great variety of phenomena and cognitive processes studied with ERP, we now tend to two particular types of signal are currently widely used and which can be approached as complementary : P300 (Fazel-Rezai *et al.*, 2012) and ErrP (Chavarriaga, Sobolewski, and Millán, 2014; Kumar, Gao, *et al.*, 2019). P300 waves are generally elicited with an infrequent stimuli with a maximum amplitude recording at the central and parietal regions of the scalp (Bashore and van der Molen, 1991) and are proportional to stimulus improbability and discrimination difficulty (Picton, 1992; Polich, Ellerson, and Cohen, 1996). Their popularity is due to the relative little amount of training necessary, depending on the complexity of the task (Guger *et al.*, 2009) and detection across diverse modalities (Fazel-Rezai *et al.*, 2012) as a robust support for the study of discriminative processes. Since frequency of appearance is a function of P300 elicitations, and their amplitudes may vary across a session, They must be measured through repeated measures and averaged (Wolpaw, Birbaumer, *et al.*, 2002). Therefore their most frequent mode of elicitation is through rapid serial presentation of an *oddball* paradigm (Kutas, Kiang, and Sweeney, 2012). *Error-related potentials*, or ErrP, are another way to bypass muscular commands and long latency responses such as in the ERN, in order to improve BCI performances (Chavarriaga, Sobolewski, and Millán, 2014; Lotte, Bougrain, and Clerc, 2015). Like P300, Errp do not necessitate training to be elicited (Trujillo and Allen, 2007) but can be modulated with levels of engagement (Hajcak *et al.*, 2005). They occur when a stimulus appear to violate prior expectations (Holroyd and Coles, 2002; Yeung, Holroyd, and Cohen, 2005) and therefore may be used in reinforcement learning policies in the form of reward or correction signals (Chavarriaga, Sobolewski, and Millán, 2014; Spüler and Niethammer, 2015). While latency may greatly vary over different tasks (Iturrate, Montesano, and Minguez, 2013), ErrP conditions can be named as *response, feedback* or *interaction ErrP*. Where elicitation occurs respectively under an incorrect behavioural response, an error-related feedback, or an incorrect stimulus (Spüler and Niethammer, 2015). They can be generally measured as difference waveform in the fronto-central regions of the cortex in relation to typical N2/P3 complex waveforms (Chavarriaga, Sobolewski, and Millán, 2014). Responses to stimulus presentations generally reflect a sequence of P200, N250 and P320. They can also be reflected in frequency increased in the *theta* band followed by a decrease in the *beta* band (Trujillo and Allen, 2007; Cavanagh, Zambrano-Vazquez, and Allen, 2012). Their reliability over time (Olvet and Hajcak, 2009) and diverse tasks (Riesel *et al.*, 2013), also in challenging conditions with higher cognitive workloads (Iturrate, Chavarriaga, *et al.*, 2012) make them equally robust ERP phenomena and complementary for multiclass classification methods as well as adaptive methods (Kumar, Gao, *et al.*, 2019).

SSEP mimick the frequency or their evoking stimulus as a sinusoidal waveform (Vialatte *et al.*, 2010) which can be sensory (eg. Visual, auditory, tactile) or somatosenroy (Erkan and Akbaba, 2018; Hill and Schölkopf, 2012; Severens *et al.*, 2010; Ahn, Kim, and Jun, 2016). Most popular types in BCI are *steady-state visually evoked potentials* (SSVEP) where several commands can be presented simultaneously as stimuli running at distinct frequencies (P.-L. Lee *et al.*, 2008; Y. Wang *et al.*, 2008). Steady states have the highest information transfer rate over other methods (Nicolas-Alonso and Gomez-Gil, 2012), require no training and which makes them extremely reliable and robust (Y. Wang *et al.*, 2008; Volosyak, 2011; Zhu *et al.*, 2010). They are however dependent of specific attendance and repetitive flickering sessions produce fatigue (Nam, Nijholt, and Lotte, 2018). SSVEP start to be noticed differently than transient states above 6Hz (Nicolas-Alonso and Gomez-Gil, 2012). Three kind of stimulus modulation are defined (Bin *et al.*, 2009) : *time* (t-VEP), *frequency* (f-VEP) and *code modulated* (c-VEP) implying that each stimulated target do not overlap in these domains for proper discrimination except for c-VEP where time and frequency become pseudo random to increase BCI performances (Nicolas-Alonso and Gomez-Gil, 2012).

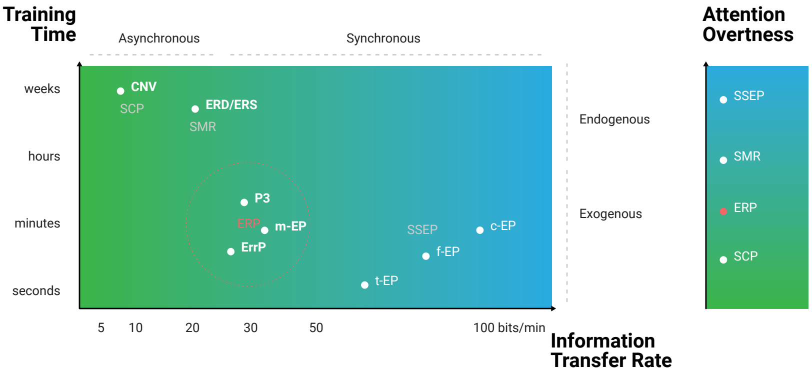

Figure 31: A synthetic 3 dimensional map of neural phenomena in BCI scenarios. Left — The axes are organised by convenience of general training time (ranging from none to weeks or even months), and information transfer rate (in bits per minute). As reported measures across literature greatly vary and are highly dependent on implementations details, the most optimistic ranges currently attained are reported. Since ITR is a function of the response time, it is very likely that endogenous responses might be used in asynchronous methods. However, Exogenous responses may be used in both synchronous and asynchronous methods. Right — the third axis allows for a convenient selection in terms of the necessary overtness of attention involved in the elicitation of the phenomena. For example, SSEP are greatly appealing due to their ITR and training performances. However they necessitate a fully overt attendance to discriminate a specific stimuli. Additionally, stimuli of greater complexity might eventually seriously diminish their advantages to ERP. In Pink are the types which appear to make more sense I the pursuit of CAAD applications. Adapted from: Nicolas-Alonso, Luis Fernando, and Jaime Gomez-Gil. 2012. “Brain Computer Interfaces, a Review.” Sensors (Basel, Switzerland) 12 (2): 1211–79. And: Lotte, Fabian, Chang S. Nam, and Anton Nijholt. 2018. “Introduction: Evolution of Brain-Computer Interfaces.” Brain-Computer Interfaces Handbook: Technological and Theoretical Advances, January, 1–8.

3.1.4 *Signals*

Since EEG would represent the main modality of acquisition in this work, this section will focus essentially on methods derived from it, while other prioritised modalities (fNIRS, Pupillometry) will be later tentatively recombined throughout the studied framework and outside of the scope of this thesis. The popular linear organisation of the processes involved in signal decoding will be followed as signal *feature selection*, *pre-processing*, *feature extraction* and *classification* to refer to the most robust and practical methods currently investigated for non-clinical conditions. Since significant advances have been made in the simplification and generalisation of such pipeline (Lotte, Bougrain, Cichocki, *et al.*, 2018) and it is very unlikely that regressional trends will emerge in the near-future, the most practical methods and baselines will be drawn.

EEG signals come with many inherent challenges. Since recordings occur at the surface of the scalp, they remain of relatively low amplitude in microvolts. The relatively low SNR being a major obstacle (Goldenholz *et al.*, 2008), even more so when recording channels are fewer (eg. with commercial devices), electrodes have poorer conductivity, as while using *dry* electrodes, and ambient recording conditions cannot be controlled, as while conducting recordings OOTL (Usakli, 2010). This makes EEG recordings prone to contain *noise* and *outliers*. While noise may be coming either from the direct environment, as from power lines or wireless communication devices for instance (Leach, 1994; Maby, 2016), or induced by the person (Jeunet, 2016) due to adversarial mental activities from a given task (eg. attention shifts due to other environmental stimuli, eye blinks and other physiological artifacts), or simply a person mental state and capacity to endure present cognitive workloads (eg. stress, fatigue, concentration, etc. . .). EEG features are also, in most cases, of *high dimensionality* and extracted from combining several of the recording dimensions (Rakotomamonjy *et al.*, 2005a). Should they be *spatial* (ie. several channels), in the *temporal* or *frequency* domains. Regarding the variability of signals, EEG are said to be *non-stationary* since they greatly vary over the time course of a session and across individuals (Klonowski, 2009; Ramadan and Vasilakos, 2017). Together with the low capacity to record larger amount of data during sessions and across populations (Lotte, 2015), BCI method generalisations become more challenging than other typical classification problems involving more static structured data such as text or natural images. Nevertheless EEG *amplitudes* remain the major feature of use in BCI, along with *band powers* (Niedermeyer and Silva, 2005) for activity peaks detection and waveforms anaylisis. Other popular use designed features are the computed spectral power from *power spectral density* (PSD) to improve multitask separability for example (Chiappa and Bengio, 2003; Millán and Mouriño, 2003), *auto-regressive parameters* (Penny *et al.*, 2000; Pfurtscheller, Neuper, Schlogl, *et al.*, 1998) for calibration, *time frequency* (Wang, Deng, and He, 2004) to augment the dimensions of local recordings, and *inverse features* (Qin, Ding, and He, 2004; Congedo, Lotte, and Lécuyer, 2006) for local assumptions of cortical activity. Throughout each of these features which cover only a part of their possible use, inherent properties may affect the entire processing pipeline.

Therefore, prior to applying any feature selection or classification methods, pre-processing is, even if minimal, always mandatory and generally includes three steps: *filtering*, *artifacts removal*, and *sampling*. One can also approach filtering throughout three types of methods which may be applied, in combination or individually, depending of the BCI conditions and the signal representations used: *temporal*, *spectral (frequencies)* and *spatial filtering*. After being digitised and amplified, since specific frequencies (eg. power lines) or frequency ranges appear to be of more specific significance given the designed BCI conditions (Ramadan and Vasilakos, 2017), it is frequent to use temporal filtering methods such as *Band-Pass* and *Notch filtering* (Lotte, Bougrain, Cichocki, *et al.*, 2018). Where *low-pass* filters would serve an anti-aliasing role of the signal and the *high-pass* and downsampling would trim the signal from other artifacts outside of the necessary frequency bands (Ramadan and Vasilakos, 2017). If remaining stationary noise persist, notch filtering can help remove archetypal frequencies such as 50, 60 Hz or their harmonics, containing strong power line residual noises (Cheveigné, 2019). Filter design types and order may differ depending on the BCI paradigm and data acquisition methods (Lyons, 2010). Temporal filters may also adapt across session in order to optimize the exploited frequency bands (Thomas *et al.*, 2011). In fact, it is common to consider these methods as part of spectral filtering methods since they actually have effects on the spectrum of the signal and restrict the EEG signals to some specific oscillatory components such as the *alpha* and *theta* bands for example. Some algorithms have been devised to adapt to the most appropriate frequency bands for each subject (Pfurtscheller, Neuper, Flotzinger, *et al.*, 1997). Depending on the kind of classifier used, one can additionally need spatial filtering methods applied to combine individual sensors signals in order to increase the SNR (Lotte and Roy, 2019), maximize classes separability (Blankertz, Tomioka, *et al.*, 2008), and even remove certain artifacts (Krusienski, McFarland, and Principe, 2012). There is a large variety of spatial filter methods (Lotte, Bougrain, Cichocki, *et al.*, 2018) among which the *Common Spatial Filter* (CSP) used for oscillatory activity (Lotte and Roy, 2019), *xDawn* (Rivet *et al.*, 2009) and *Fischer Spatial Filter* for ERP (Hoffmann, Vesin, and Ebrahimi, 2006). We can also note current adaptive forms of these methods as *adaptive xDawn* (Woehrle *et al.*, 2015) for ERP-based BCI and *Filter Bank CSP* (FBCSP) to improve subject-specific calibration (Ang, Chin, Zhang, *et al.*, 2008; Ang, Chin, Wang, *et al.*, 2012).

Finally, artifacts can be legion and range from environmental noise to intrinsic signals (Sweeney, Ward, and McLoone, 2012). Therefore, some artifact rejection may still be necessary in order to filter out remaining ones such as muscle activity, occular movements or even heart beat (Fatourechi *et al.*, 2007). Artifacts removal methods may range from simple regressions combining both main signals and assumed artifactual ones (eg. EEG + EOG) as the popular baseline for comparison, *wavelet transform* in combination with complementary components analyisis (eg. ICA), to *Blind Source Separation* (BSS) as unsupervised methods — among which the most famous are *Principal Component Analysis* (PCA), *Independent Component Analysis* (ICA), *Canonical Correlation Analysis* (CCA), and *Source Imaging* Based Methods —, *Empirical Mode Decomposition* (EMD), *Sparse Decomposition Analysis* (SDA) and BSS hybrid methods (Sweeney, Ward, and McLoone, 2012; Jiang, Bian, and Tian, 2019). These different filtering methods may also be then implemented with different optimization approaches such as *adaptive*, *wiener* or *bayes filtering* (He *et al.*, 2005). No general strategy currently exists but in the case of a few channels and a computational cost low enough to perform online, EEMD-CCA represents a computationally cheap and stable method (Sweeney, Ward, and McLoone, 2012; X. Chen *et al.*, 2019). But since mostly performant for muscle artifacts, it can be compared with its more versatile and costy baseline : EEMD-ICA.

Even though current classification methods tend to embed feature extraction within classification (Lotte, Bougrain, Cichocki, *et al.*, 2018; Mladenović, Mattout, and Lotte, 2017), certain independent features remain necessary for a given classifier in order to represent signals in a compact and specifically structured fashion (Bashashati *et al.*, 2007). Among the most common types of features are *band power* for oscillatory activity (Herman *et al.*, 2008; Brodu, Lotte, and Lécuyer, 2011) and time points especially used for ERP scenarios once an averaged response has been computed across trials (Blankertz, Lemm, *et al.*, 2011; Lotte, 2014). As in each and every signal processing steps, adaptive feature extraction methods may also be envisioned, should they not add too much of a re-calibration cost in the pipeline and support the classifier performances (Vidaurre and Schlogl, 2008). Among other popular features are as well *autoregressive parameters* and *wavelet methods* (Brunner *et al.*, 2011) which also have their own adaptive approaches for online scenarios (Schlögl, Vidaurre, and Müller, 2010; Costa and Cabral, 2000; Satti *et al.*, 2010). Ultimately, in the case of the most recent classification methods later mentioned, features as *connectivity-based* (Lotte, Bougrain, Cichocki, *et al.*, 2018), or *array-based* features as *tensors* and *covariance matrices* as linear combinations of diverse sources (Cichocki, 2013; Congedo, Barachant, and Bhatia, 2017).

Given previously mentioned BCI conditions to enable literacy, adaptive and robust classification methods which can start from little amount of available data are of main interest here due to the challenging conditions of data acquisition OOTL, and the relatively new acquaintance of research and users foreign to BCI with these techniques. Which immediately allows for a clear distinction from typical deep learning methods (Lotte, Bougrain, Cichocki, *et al.*, 2018) even with the most advanced ones (Gu *et al.*, 2020; Craik, He, and Contreras-Vidal, 2019; Roy *et al.*, 2019; X. Zhang *et al.*, 2019). Even though several methods for data augmentation have been mentioned through transfer learning or generative models (Coelho Rodrigues, Congedo, and Jutten, 2020; Abdelfattah, Abdelrahman, and Wang, 2018; Gu *et al.*, 2020). In fact, *shallow* CNN approaches and other relatively compact hybrid CNN combinations have shown to be promising (Schirrmeister *et al.*, 2017; Tuleuov and Abibullaev, 2019) for *subject-independent* generalisations and fairly low amount of necessary training dataset. Though, they still require initial calibration for their remaining parameters but can operate without spatial or spectral filtering (Lotte, Bougrain, Cichocki, *et al.*, 2018). Nevertheless, their training would remain offline, supervised, and improved calibration over time would be done through typical batch training (Woehrle *et al.*, 2015). The former baseline of deep learning approaches is generally linear *Support Vector Machines* (SVM) while their robustness and low level of calibration parameters allowed for better generalisation (Lotte, Congedo, *et al.*, 2007) and can also be used with *ensemble methods* for tackling non-stationarity issues across sessions (Rakotomamonjy *et al.*, 2005a; Li and Zhang, 2010). In fact, ensemble methods have been and remain widely useful in classification methods at large to capture greater variance in diverse BCI paradigms (Soria-Frisch, 2012; Nguyen, Karavas, and Artemiadis, 2019). SVM have also been subject to several variations in adaptive methods and tensor-based versions (Lotte, Bougrain, Cichocki, *et al.*, 2018; Xu *et al.*, 2019) but remain computationally costy to retrain for an online mode. Other kind of linear classifiers based on decision boundaries have remained an active baseline for other kind of emerging trends. Among the most popular, the main references are the *Linear Discriminant Analysis*, or LDA (Nicolas-Alonso and Gomez-Gil, 2012) and its improvement to handle low amount of initial data samples and robustness with *shrinkage* method, or sLDA, (Blankertz, Lemm, *et al.*, 2011) and its incremental adaptive methods for online classification (Vidaurre, Kawanabe, *et al.*, 2011; Vidaurre, Schlogl, Cabeza, *et al.*, 2007).

Riemannian Geometry Classifiers (RGC) have appeared to become a new reference in terms of compacity (no need for spatial filtering) robustness to outliers and accuracy on little data with very *few-to-zero* calibration parameters depending on the pipeline chosen (Congedo, Barachant, and Bhatia, 2017; Yger, Berar, and Lotte, 2017). Instead of using typical time points or band power as data representations, RGCs use covariance matrices to be discriminated by separating their *riemannian distance*. Among the different RGC approaches, two popular ones are defined by using a *Minimum Distance to the Mean* (MDM), and its *Fischer Geodesic* version (FgMDM). While the second one is intended to improve the initial separability of classes by using geodesic filtering (Barachant, Bonnet, *et al.*, 2010). An adaptive approach for online learning of the FgMDM has been suggested to improve robustness and separability over sessions (Kumar, Yger, and Lotte, 2019) and competes with previous adaptive attempts as in (Barachant and Congedo, 2014). Regarding cognitive and affective states classification, which are dependent on oscillatory activity signals rather than time points, and useful in passive BCI conditions, a similar competition between CNN and RGC can be found regarding the approach to choose, given the amount of available training data, and against the standard baseline usually constituted of a *filterbank CSP* (FBCSP) and LDA (Appriou, Cichocki, and Lotte, 2020). Since emotion estimations seem to remain an important challenging task, *workload estimations* appear to be achievable in an offline mode to infer on next sessions parameters. While CNN approaches offered good subject-independent performances with few subject data, RGC implementations with filter bank methods (eg. FBFgMDM) inserting more spectral information for classification suggested better subject-specific calibrations (Appriou, Cichocki, and Lotte, 2020). It is also worth considering more sophisticated methods implementing offline competing techniques of classifiers to perform at the best amount of available data. Or in the case of expected prolonged BCI use for a user, to use a robust generic and subject-independent framework which would be fine-tuned to the user incrementally in order to reduce calibration time (Kindermans *et al.*, 2014). Finally, It is also worth mentioning that decision methods, based on classified outputs, can be also made adaptive on judging by the speed/accuracy tradeoff of the classification or weighting on the user's mental state (Mladenović, Mattout, and Lotte, 2017), as one can easily modulate thresholds on methods such as averaging or summing intersections of results.

3.1.5 *Measures*

BCI measures greatly vary among its numerous designs and conditions. However, performance evaluations must be balanced from its two ends: evaluated from a *user's perspective*, from the designed conditions and *signal processing perspective* and *compound measures* from the interface as whole.

Since BCI use is aimed at humans, it is important to start by understanding the general purpose of the targeted BCI and find a proper population to evaluate its overall performances, as conditions and expectations may vary greatly among clinical and commercial use, healthy and non-healthy individuals, specific or grouped tasks (Rhiu *et al.*, 2018). The *usability* measures serve this general purpose (Wilson, 2009) along categories such as *efficiency*, *effectiveness* and *satisfaction* with *subjective* and *objective* measures. While objective ones make use of both covert and overt responses during interaction conditions, subjective measures happen afterwards (Nielsen and Mack, 1994). Among most popular subjective measure exist questionnaires such as the *Nasa Task Load Index*, or NASA-TLX (Cao *et al.*, 2009) evaluating mental workloads based on multiple dimensions, the *Visual Analogue Scale*, or VAS (Ohnhaus and Adler, 1975) to asses user's feelings, Questionnaire *for Current Motivation*, or QCM for motivational factors (Rheinberg, Vollmeyer, and Burns, 2001), or simple assessment surveys such as SUS and USE (Bangor, Kortum, and Miller, 2009; Lund, 2001) to measure user's motivations. A myriad of such evaluations exists and serves as an approach to subjective measures from different angles in various BCI conditions (Choi *et al.*, 2017). However, subjective measures are also subject to many *biases* (Rhiu *et al.*, 2018) and are generally more useful in the case of longitudinal studies to reflect behavioural trends and HMI questions. For evaluations at the scales of an individual or a small group, practical non-invasive methods such as EEG (Frey *et al.*, 2016) and fNIRS may be used to extract objective measures from ongoing activity and adapt the BCI retrospectively (Stein *et al.*, 2017). Consequently, objective measures aim to address questions of co-adaptations as previously mentioned [4]

3.1.6 *Framework*

Within the scope of pursued CAAD applications, and from previous assessments made on BCI methods for *acquisition*, *literacy*, neural *phenomena*, *signals* processing and *measures*, one can scheme a general hybrid framework which encompasses certain prior conditions and a research agenda which spans also across the outlook of the present work (see **??**).

Given previous considerations on modeling and neural potentials [5]

Through this series of iterative experiments , the ambition is twofold : probing for research questions, and develop a machine enabling to ask them. The general vector followed by this series is to progress from generic methods about spelling to progressively approach the developed vocabulary in the previous chapters and test their applicability with BCI techniques. Accordingly, all experiments are based upon a visual ERP-based BCI (see Figure 32), are described and organised through the following sections : - *Question*: what is to be probed - *Tokens*: The discretisation of objects to present - *Presentation*: How tokens are presented in a visual sense - *Acquisition*: The data acquired while sensing - *Discrimination*: The decoding and encoding of discriminative patterns - *Generation*: The exploitation of the produced encoder - *Results*: Commented results and discussed contribution to the question. Their goal is primarily exploratory. Additional documentation regarding custom hardware and software developments for didactic and practical purposes is provided afterwards in the *Appendix*. Similarly, additional content regarding the experiments can be found there - *Code*: Selected codes and data for demonstration and reproducibility purposes of particular steps - *Production*: Additional material and artefacts produced through the experiments for documentation and demonstration purposes. The following experiments are hereafter described and follow a sequential order of research.

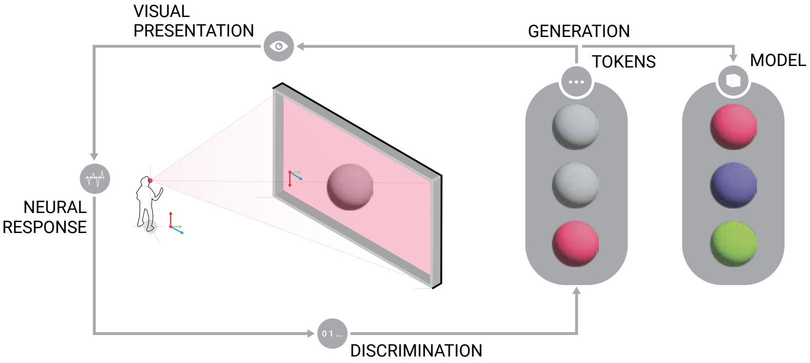

FIGURE 32: Basic diagram of an exogenous BCI based on visual ERP in a closed loop. Tokens are being generated for visual presentation to trigger a typical neural response in form of ERP which features are being discriminated to label and select tokens to be aggregated in a model over time.

3.2.1 *Generalizing a P300-BCI Word Speller*

Next page: A custom visual p300 BCI implemented for the research.

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In the context of communication, *Brain-Computer Interfaces* (BCI) models are great examples of correlating two dissociate phenomena to re-establish a communication bridge between an emitter, usually unable to communicate in physical conventional means (eg. voice or gestures), and a receiver being able to receive and decode a message (Wolpaw, Birbaumer, *et al.*, 2002). In a most general perspective, the two phenomena mentioned as being decoded/encoded would be any sensory stimuli from the world, and neural patterns to be found and correlated in specific domains (ie. Time, Frequency and/or Space). Such models have been proven to be effective in many applications, to decode and encode personal communication loops between humans (Rao *et al.*, 2014) and humans between machines (Nam, Nijholt, and Lotte, 2018; Lebedev and Nicolelis, 2006).

Among the most well defined BCI used for that purpose, one can take as a classical example, the task of spelling characters to form words and sentences. In such case, vision becomes the main modality which replaces speech. BCI *Spellers* (Farwell and Donchin, 1988; Rezeika *et al.*, 2018), by making use of a handful group of well identified and studied neural patterns such as *Event-related Potentials* (ERP), *Event-Related Desynchronization/Synchronization* (ERD/ERS), or *Error-Related Potentials* (ErrP) (Wolpaw, Birbaumer, *et al.*, 2002; Chavarriaga, Sobolewski, and Millán, 2014; Cecotti, 2011), and visual presentation techniques such as *Rapid Serial Visual Presentation* (RSVP) (Kutas, Kiang, and Sweeney, 2012; Spence and Witkowski, 2013) in order to re-establish communication, are demonstrating great capacities in learning, from one or several users (Zanini *et al.*, 2018), the modalities of ***articulating visual characters without any explicit grammar*** to form meaningful words and sentences. That is to say: given a set of such visual tokens without explicitly presenting any schemes on how to articulate them together, meaningful discriminations might appear successively to form words and sentences conveying rich semantic content.

While such interfaces have already demonstrated to be furnishing gaps in eventual lacks of capacity in writing and talking as in natural communication, it might be also proven of interest for the meaningful articulation of various parts together that we might provisionally label *modeling*. And in the context of computer-aided modeling, an analogy to such models might also be proven of great capacity when interfacing human and machine intelligence features together in a computational loop. To pursue this idea, and while keeping in mind that cognition as we know it remains an embodied phenomenon, and neural cognitive patterns are never fully caused by a unique sensory channel, this research will consider ***visual information as the primary means of producing articulations and architectonic relations between things to form objects*** (Humphreys and Riddoch, 2006) and seek the following question: ***Can such computational communication model be generalised as simply as a visual token discrimination technique to study its potentials in architectural and design modeling?*** Through the study and generalisation of a classical gaze-based BCI spelling model, this experiment will focus on its reproduction and the generalisation of its methods for a later research development on design and architectural modeling cases.

Tokens

The visual spelling of characters forming words through a BCI model (see Figure 33 for illustration) is a protocol established by Farwell and Donchin in the late 80's (Farwell and Donchin, 1988) using the *Oddball paradigm* (OP) (Kutas, Kiang, and Sweeney, 2012; Squires, Squires, and Hillyard, 1975) and became a benchmark itself for studies related to an ERP component occurring along the cognitive process of decision-making (Donchin, Spencer, and Wijesinghe, 2000), originally known to manifest in a time window situated around 300ms after the occurring of a peculiar stimulus (P300). Although there are currently many existing variations (Yeom *et al.*, 2014), its primary form consists in a 6x6 matrix of 36 alphanumeric characters in the Latin/Roman alphabet (*A* to *Z* and *0* to *9*) where rows and columns are randomly flashed in a repetitive sequence for correlating each character of a given word with an elicited P300 wave. Flashed rows/columns containing the specific character during each sequence are supposed to elicit the peculiar electric wave pattern recorded from the neural activity of a person watching the RSVP session. Since the P300 wave pattern is found to be locked in time (Luck, 2012), it can then be used for the purpose of visual spelling and be subject to the training of classifiers for correlating peculiar wave patterns with relevant characters. As such combination became a typical model for the organisation of visual token to be presented, it can also be referred to as the *Row Column Paradigm* (RCP).

Figure 33: A typical gaze-based BCI, with RSVP OP, spelling session where a user is looking at a rapid presentation of randomly flashed rows and columns of characters while recording neural activity. Both software and hardware were designed along the research to balance between practicality and reliability in an Out-Of-The-Lab environment.

The chosen version of the RSVP method for spelling is as follows: For a given word, the general sequence is made of three main steps : 1- a visual cue for the current character to discriminate, 2- the flashing of tokens, and 3- a pause before jumping to the next character (see Figure 34). The time periods set for these recording sessions were 2500ms for the cue period T_C , 100ms for the flashing of a token T_F and 75ms for the non-flashing period T_{NF} , before a new token is flashed, followed at the end of the tokens presentation step by 2500ms again for pausing before going to the next character. The necessary non-flashing periods are set to clearly identify a pattern in the signal with its preceding stimuli as close in time as possible and without overlaping already with another wave pattern possibly following next (Luck, 2014). The timing of the periods, are set here as initial parameters values for future software developments as an adaptive RSVP based on user visual preferences, and based on previous stable similar research (Lotte, Congedo, *et al.*, 2007; Rakotomamonjy *et al.*, 2005b). Nevertheless, they should not be considered as a general optimum, but rather as initial settings, since performances may vary among both users and sessions.

Figure 34: General sequence of the spelling session for a given word (here: COGNIZABLE). For each character, the three main steps occur successively. 1). Left: Cue, The character to spell is shown for a fix amount of time. 2). Middle: Tokens, a random sequence of rows and columns is flashed with fixed periods of flashes and non- flashes. 3). Right: Pause, a short non-flashing period of time occurs before going to the next character to spell while applying the same sequence until the last character.

During the tokens presentation step, the alphabet matrix is recombined in a set of 12 rows and columns (RC), each one containing 6 characters of the matrix. Before the flashing sequence, RC is shuffled in a random uniform fashion and each element of RC is then presented such that the character to discriminate will appear twice on screen in a row and a column. This procedure is repeated 15 times for each character such that there are 180 presented tokens to be discriminated for each tokens presentation (see Equation (1)). The amount of repetition is based on the same principles than for setting the time periods and the RC flashing remains relative to the alphabet matrix size, such as for a matrix A containing $i * j$ characters, we would have Equation (1). And given n as a repetition parameter, we would obtain the following distribution of RC : Equation (2). A synthetic picture of the process can also be visualised as in Figure 35.

$$A = \begin{vmatrix} C_{00} \ldots C_{0j} \\ \ldots \ldots \ldots \\ C_{i0} \ldots C_{ij} \end{vmatrix} \tag{1}$$

$$RC = n * RandU\{\ [C_{00}, \ldots, C_{0j}], \ldots, [C_{i0}, \ldots, C_{ij}], [C_{00}, \ldots, C_{i0}], \ldots, [C_{0j}, \ldots, C_{ij}]\ \} \tag{2}$$

For all recording sessions, a word length of 10 characters was chosen. Most BCI spellers tend to gather training data around words length of 5–6 characters due to challenges of maintaing attention during RSVP tasks, among which repetition blindness or attentional blink (Arnell and Shapiro, 2011). Since targeted applications are for more complex and time-extended interpretations of such paradigm, it was chosen to double this length during recordings and progressively reduce it during classification training until a satisfying accuracy is reached. Given the word length w, the total session time T_S is then Equation (3).

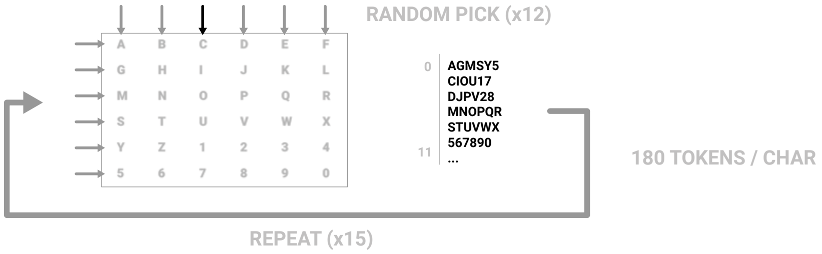

Figure 35: Random picking of a row or column to be flashed as a stimuli during spelling session. Each row and column is indexed from 0 to 11. Index 12 is reserved for non-flashing periods. The random picking sequence is repeated 15 times to finally obtain a total of 180 tokens to be consecutively flashed per character.

$$T_{\mathrm{s}} = w * (T_{\mathrm{c}} + (T_{\mathrm{f}} + T_{\mathrm{nf}}) * (i + j) * n + T_{\mathrm{p}}) \tag{3}$$

Which gives here a session time of approx. 365 seconds, given eventual latencies, and a total of 1800 epochs for all 10 characters. Each session is recorded at approximately 60 Hz and each data point P is represented with a timestamp T, an index IJ in the consecutive list of rows and columns of the alphabet matrix, and a marker M depending on wether or not the flashed token at T contains a target character, such that $P \Rightarrow (T, IJ, M)$. In Table 1 is a sample of the structured dataset as a result.

Timestamp (T)	RC Index (IJ)	Marker (M)
2019-04-30 11:11:46.324218750+02:00	12	0
...	...	...
2019-04-30 11:11:54.644531250+02:00	10	2
...	...	...
2019-04-30 11:11:54.742187500+02:00	10	1
...	...	...
2019-04-30 11:11:54.761718750+02:00	12	0

Table 1: Sample of a recorded time series during one session and showing the data structure for each data point. From Left to Rigth: the timestamp T, the RC index IJ (from 0 to 11, 12 represents a pause or a non-flashing state), the marker M (0: non-flashing, 1-non-target, 2-target character).

Presentation

There is a limited set of well-studied paradigms in correlation with known ERP but which allows for a wide range of inferences on cognitive processes such as inattentive auditory processing, selective attention, stimulus evaluation, working memory updating, movement preparation and inhibition, error processing memory, language processing, face processing or even mental chronometry (Kutas, Kiang, and Sweeney, 2012).This research focuses on a well-studied paradigm used to elicit a P300 wave and based on the principle of discrimination: the *Oddball Paradigm* (OP). The OP is a typical RSVP task with frequent, random, deviant stimuli: the *oddball* (Kutas, Kiang, and Sweeney, 2012). These peculiar stimuli are thereby employed to detect the elicitation of an ERP. In the case of a visual OP, a series of self-similar events are shown at fast pace in sequences of consecutive flashes of a few milliseconds (see Figure 36).

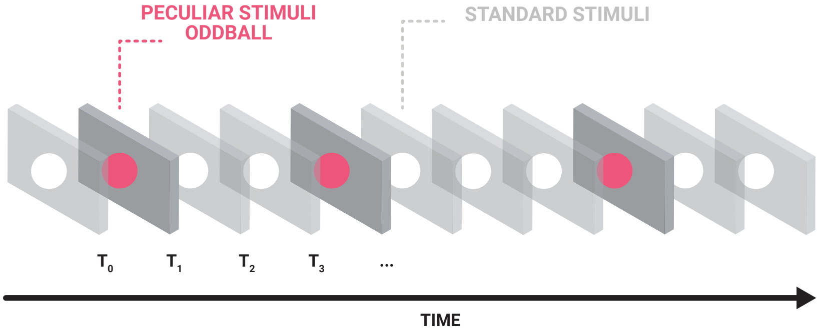

Figure 36: A typical visual OP in a RSVP task to elicit ERPs. Each stimulus presentation epochs and in-between epochs consist of a few milliseconds in the time domain and in the elicitation range of the studied ERP wave. Epochs share similar properties but one among all : a peculiar stimulus used as an oddball to elicit the ERP discriminative pattern (represented here by a pink dot).

In the scope of implementing such paradigm used in ERP for design purposes, and in the present case of study, the P300 speller already possesses many implementations of the RSVP OP (Donchin, Spencer, and Wijesinghe, 2000). It typically consists of a matrix of characters as shown previously. Each row or column is flashed as a stimulus, according to the OP as shown in Figure 37. The oddball is then the character to be spelled to form a word, with the probability of being contained in the presented row or column. A digital representation of this matrix is composed of a list of strings making rows and columns, as well as an index ranging to the length of the list in order to efficiently retrieve and correlate the stimulus. In addition to the potential behaviours mentionned above and which would eventualy lead to errors, one can add the obvious but often disregarded rise of frustration and decrease of attentional ressources coming from slow communication flows (Townsend *et al.*, 2010). Another source of errors inherent of this technique comes from the adjacency of similar target and non-target characters from successive rows and/or columns (Fazel-Rezai, 2007). Much early evidences also emphasizes that P300 amplitudes vary inversely proportional with the probability that a user might discriminate an eliciting event. A completely predictable event generally accounts for fewer amplitudes, and uncertain occurences for larger ones (Sutton *et al.*, 1965; Donchin, Kubovy, *et al.*, 1973; Friedman, Hakerem, *et al.*, 1973). This can be greatly influenced by the manipulation of stimulus sequences in their *Prior Probability* (PP), to consequently affect the user's *Subjective Probability* (SP), or expectancy, of stimulus discrimination (Duncan and Donchin, 1977; Polich, Brock, and Geisler, 1991). While the later would be hard to model appropriately, the former would help to build a better correlation model between a stimulus and an elicited neural phenomena.

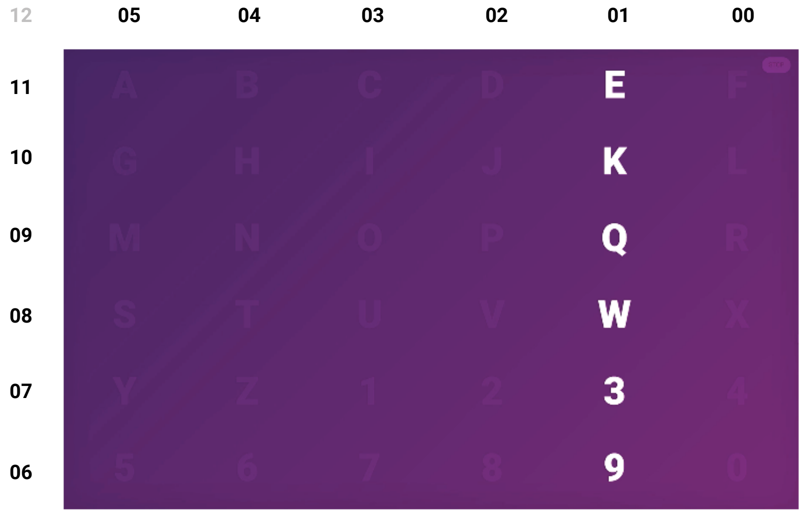

Figure 37: The developped rendering on screen of the character matrix. Each row and columns is flashed separately in a RSVP manner and are indexed for retrieval and later classification.

While designing the presentation of a task, it might be hard and even sometimes countereffective to oversimplify the information to be presented. One might gain in discerning what is really being discriminated by a user but the further it goes into simplifying a task, the less it becomes relevant to the understanding of more complex and practical ones. While it is an obvious and necessary trade-off in scientific methods of measurements and reproducibility, another obvious choice for applicative and transferred methods would be to favour the time and frequency structure of the RSVP OP task in order to manipulate the PP ratio in an adaptive fashion for the user. Several axis of research have been drawn to progress on the design of adaptive BCI for better applications (Mladenovic *et al.*, 2020; Cecotti, 2011; Mainsah *et al.*, 2015). Since the RCP is a model specifically designed for the task of spelling characters, it would not be relevant to maintain it as such for further research. In contrary to the underlying presentation structure of the RSVP OP which provides for greater capabilities, while taking into account the necessity to adaptivity and the drawbacks that discrete flashes may present. Based on Equation (3), a generalized PP formula for RSVP OP tasks would then be Equation (4). Where T is the total amount of flashed target stimulus, NT containing both the total amount of non-target flashed ones and the non-flashed stimulus (ie. blanks). The total amount accounts for shuffled sets of stimuli repeated n times for a character to be discriminated (eg. As represented in the precedent section by RC). Increasing $\mathsf{P}(T)$ would be made by increasing the amount of T across this character set, and in a random fashion, while avoiding adjacencies, given the probability of two consecutive flashed target Equation (5). Since manipulating $\mathsf{P}(T)$ directly influences $\mathsf{P}(T \mid T)$, a permutation rule of non-consecutive events should be studied as long as Tremains small enough to also allow for any kind of non-consecutive patterns.

$$\mathsf{P}(T) = \frac{T}{T + NT} \tag{4}$$

$$\mathsf{P}(T \mid T) = \mathsf{P}(T) * \frac{T-1}{(T+NT)-1} \tag{5}$$

Acquisition

For the recording of large P300 potentials evoked by RSVP, 3 devices are initially used per user to compare discriminators and device configurations (Barachant, 2019a,b). The following configurations have been used: *Muse 2*[6]: sampling frequency: 256 Hz /channels: TP9 , AF7 , AF8 , TP10 - Muse 2 with an extra electrode (*Muse2+*): sampling frequency: 256 Hz /channels: TP9 , AF7 , AF8 , TP10 , POz - *OpenBCI*[7]: sampling frequency: 125 Hz /channels: FC5 , FC6 , C3 , Cz , C4 , CP1 , CP2 , P3 , Pz , P4 , PO3 , POz , PO4 , O1 , O2 , Oz . The channels are referred to the electrode placements according to the international placements *1005* and *1020* (Sharbrough *et al.*, 1991). The recorded signals are digitised at their device's sampling frequency. Each signal is then filtered with an eighth-order bandpass filter with low and high cut- off frequencies of 0.1 and 20 Hz (Figure 38).

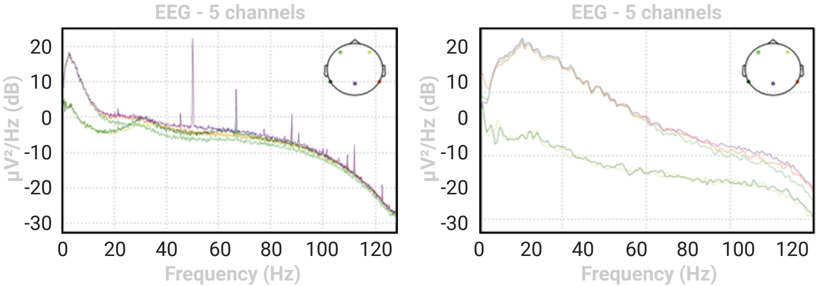

FIGURE 38: The power spectral density of acquired data through one of the tested devices (Muse 2 +). Left: before filtering. One can observe a DC Drift from the signal, a 50 Hz Power Line Noise (Europe), other frequencies and their harmonics coming from various ICT devices in the physical surroundings of the place of acquisition. Right: after filtering. Here, AF7 and AF8 electrodes (top left and right of the head diagrams above) generally still have some noise but remain decent to exploit the signal.

After a time segmentation of -0.100 to 0.700 s onset visual stimulus, each signal is down-sampled to the high pass of the filter (ie. 20 Hz). Most ERP components are found in signal frequencies below 20 Hz. (Luck, 2014). As a general rule-of-thumb, eye-blinks artifact rejection, along with other eventual muscular movements, is applied for amplitudes above 75 Microvolts. Although there exists many methods to automate and adaptively remove occular artifacts (Schlögl, Keinrath, *et al.*, 2007), this method will remain at a simple pre-processing stage. During training, a last preprocessing step is added to the segmentation by labelling epochs with binary values depending of the occurence during a target flash/token or not. All epochs can then be averaged and plotted according to these conditions and allow to visualize wether or not the chosen acquisition method and device configuration allows for the finding of P300 patterns. When reference electrodes were placed on the forehead (FPz), in contrary to traditional ERP placements (Oostenveld and Praamstra, 2001) it was noted to be inversing the polarity of detected potentials (Krigolson *et al.*, 2017). See Figure 39, Figure 40, and Figure 41.

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[6] link

[7] link and link

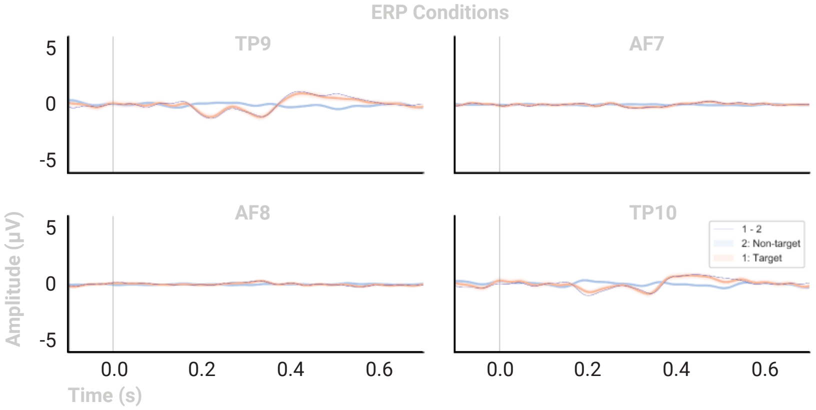


Figure 39: Plotting of averaged epochs for the Muse 2 configuration. A clear pattern happens both at TP9 and TP10 between approx. 0.2 s and 0.5 s. It is to be noticed that another ERP component occurs circa 0.2 s.

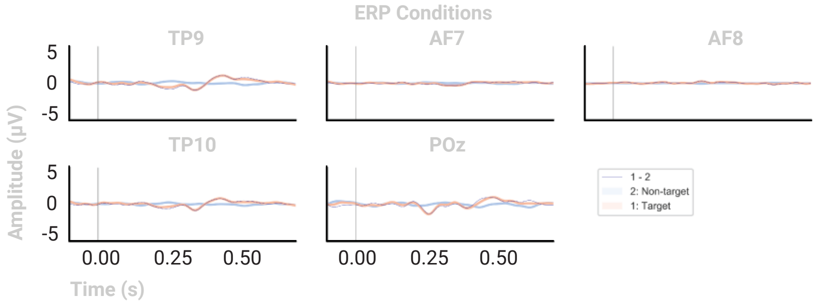


Figure 40: Plotting of averaged epochs for the Muse 2+ configuration. Similar patterns occur than with the Muse 2. With the addition of a clear pattern occuring at POz between approx. 0.25 s and 0.5 s.

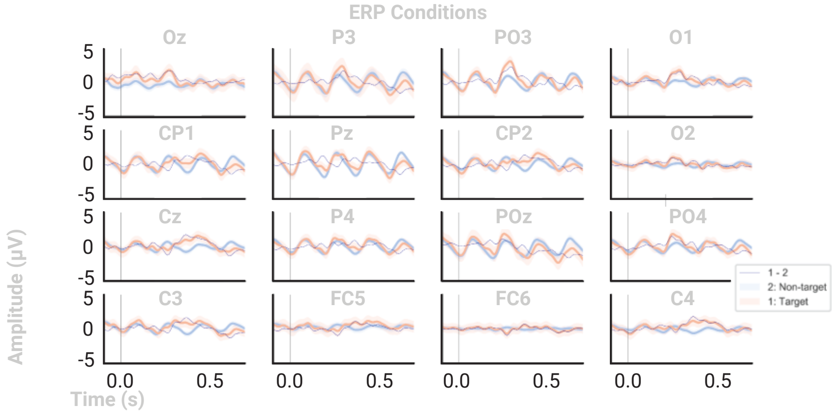


Figure 41: Plotting of averaged epochs for the OpenBCI configuration. More electrodes mean slightly more complex wave patterns. But one can see distinctive peaks between approx. 0.2 s and 0.4 s in the channels FC5, FC6, Oz, O1, O2, PO4, PO3.

Discrimination

From a given dataset of 5 recording sessions across several days for each user, discriminators are trained and evaluated while decreasing the length of the dataset. This is done by segmenting the dataset by chunks of characters being spelled and progressively decreasing the amount of spelled characters to be used for training. The assumption is to observe the stability of compared discriminators over lesser and lesser amount of data, their capacity to handle EEG and ERP features (Lotte, Congedo, *et al.*, 2007), as well as the proper amount of data to maintain for variance and later generative sessions. The following evaluations are done for three tested configurations/devices per user (Figure 42, Figure 43, Figure 44). For this purpose, 6 discriminative pipelines (Barachant, 2019b) have been chosen for their known robustness (Lotte, Bougrain, Cichocki, *et al.*, 2018; Lotte, Congedo, *et al.*, 2007) and set with default parameters (**??**). For the same reasons and starting with very few amounts of data, deep learning methods have not been included for comparison. The described procedure reflects a generalisation applied individually for each user/device configuration and the most appropriate discriminator and dataset length might vary from one configuration to another. Here, it is assumed that further training and model developments are bound and dedicated to a single user, but the methods will remain generic.

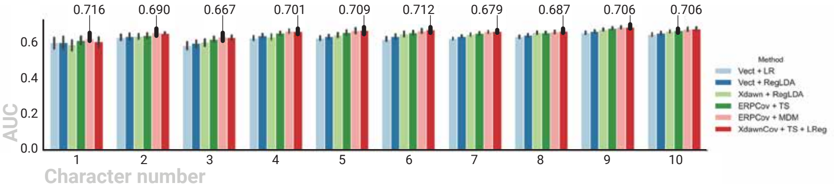


FIGURE 42: Muse 2. No significant difference in training for only 4 channels. Although an increase in accuracy might appear for methods using covariance matrices when more training data is applied.

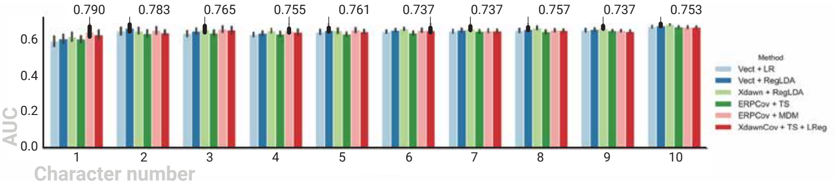


FIGURE 43: Muse 2+. Similar remarks than previously with a general increase in accuracy for all methods.

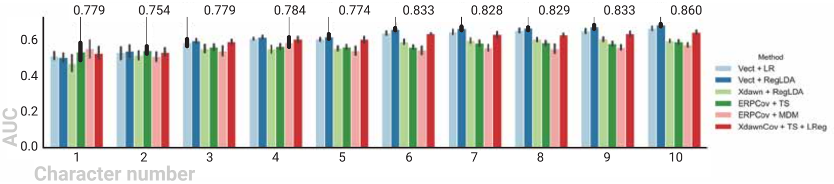


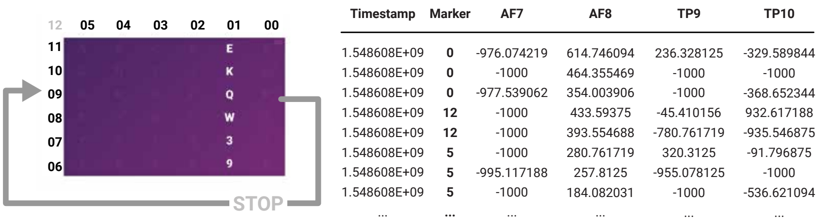
FIGURE 44: OpenBCI. After 5 characters, the discriminator Vect + RegLDA remains superior to others with a AUC score of 0.86 accuracy for 10 characters. The difference in evolution with the other device might be due to the capacity to handle increased noise. Three methods start to stand out employing Vectorization, Linear Regression and/or Covariances (ie. Vectorization and Logistic Regression, Vectorization and Linear Discriminant Analysis, Xdawn Covariance Matrix with Riemannian Tangent Space and Linear Regression).

Pipeline	Ordered Components	*Parameter*= Value
Vect + LR	1. Vectorizer	na.
	2. Standard Scaler	*Mean centering*=True, *Unit standard deviation*=True,
	3. Logistic Regression	C=0.1, Class weight=None, Dual formulation=False, Fit intercept=True, Intercept scaling=1, Max iter=100, Multi class='ovr', Penalization=‘l2', Solver='liblinear', Tolerance=0.0001
Vect + RegLDA	1. Vectorizer	na.
	2. Regular Linear Discriminant Analysis	Shrinkage='auto', Solver='eigen', Store covariance=False, Tolerance=0.0001
XDawn + RegLDA	1. XDawn	Baseline Covariance=None, Classes=[1]
	2. Vectorizer	na.
	3. Regular Linear Discriminant Analysis	Shrinkage='auto', Solver='eigen', Store covariance=False, Tolerance=0.0001
ERPCov + TS	1. ERP Covariance Matrices	Estimator='oas'
	2. Riemannian Tangent Space Projection	Metric='riemann', Tangent Space Update=False
	3. Logistic Regression	C=0.1, Class weight=None, Dual formulation=False, Fit intercept=True, Intercept scaling=1, Max iter=100, Multi class='ovr', Penalization=‘l2', Solver='liblinear', Tolerance=0.0001
ERPCov + MDM	1. ERP Covariance Matrices	Estimator='oas'
	2. Minimum Distance to Mean	Metric='riemann'
	3. XDawn Covariance matrices	Spatial Filters=True, Estimator='oas', Number Filters=2, Xdawn Estimator=‘scm'
XDawnCov + TS + LR	1. Riemannian Tangent Space Projection	Metric='riemann', Tangent Space Update=False
	2. Logistic Regression	C=0.1, Class weight=None, Dual formulation=False, Fit intercept=True, Intercept scaling=1, Max iter=100, Multi class='ovr', Penalization=‘l2', Solver='liblinear', Tolerance=0.0001

Figure 45

Generation

During the RSVP session with similar parameters and acquisition device than the training, a timeseries is recorded while the user is visually spelling a word with n-characters. The recording stops when the user interrupts the session and the dataset is trimmed by chunks of recorded character-sessions. Given that the data is being indexed by flashed row/columns but is not being labelled (Figure 46), it is subject to similar preprocessing than for training before sent to the trained predictor. Each chunk is then used to predict a character to be concatenated and to finally form the guessed word. In order to return a guessed character, the classes generated by the predictor for each epoch is associated with its flashed row/column index. For each character session, the row/column which appears the most is selected to be the final guessed character (Figure 47). Such that for N-flashing sequences of n-character sets, the target character E corresponds to the maximum summation of N-intersections of all n-character sets A as in Equation (6).



Timestamp	Marker	AF7	AF8	TP9	TP10
1.548608E+09	**0**	-976.074219	614.746094	236.328125	-329.589844
1.548608E+09	**0**	-1000	464.355469	-1000	-1000
1.548608E+09	**0**	-977.539062	354.003906	-1000	-368.652344
1.548608E+09	**12**	-1000	433.59375	-45.410156	932.617188
1.548608E+09	**12**	-1000	393.554688	-780.761719	-935.546875
1.548608E+09	**5**	-1000	280.761719	320.3125	-91.796875
1.548608E+09	**5**	-995.117188	257.8125	-955.078125	-1000
1.548608E+09	**5**	-1000	184.082031	-1000	-536.621094
...	**...**	...	...	...	...

FIGURE 46: Data acquisition for offline prediction of a word with n-characters. Left: The UI showing the RSVP session. Right: the recorded and indexed data.

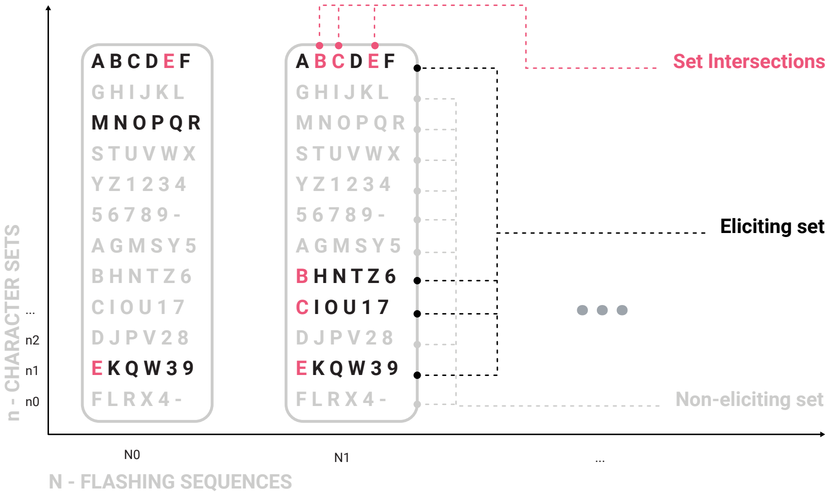


FIGURE 47: Ilustration of the most probable discriminated character found by set intersections, among n character sets and N flashing sequences.

$$E = \max \sum_{j=1}^{N} \cap_{i=1}^{n} A_i \tag{6}$$

Results

The minimum accuracy score for the training of discriminators is initiated at a minimum of *0.7* of AUC accuracy for the training on *10*-characters words. Once reached, the offline prediction for spelling a word of *n*-characters can start and the guessed word returned by the predictor is modified by the user as a post-labelling of the data if containing erroneous characters (Figure 48). The newly labelled data is then added to the previously compiled dataset of the user to perpetually train the pool of discriminators in the background. Such generative spelling session may continue, and by doing so, augment the existing dataset and increase the chances of greater discriminative accuracy for a given user (Figure 49). Which also leaves the opportunity to include further discriminative pipelines later in the study, such as the ones including deep learning models and requiring significantly more data to perform (Schirrmeister *et al.*, 2017).

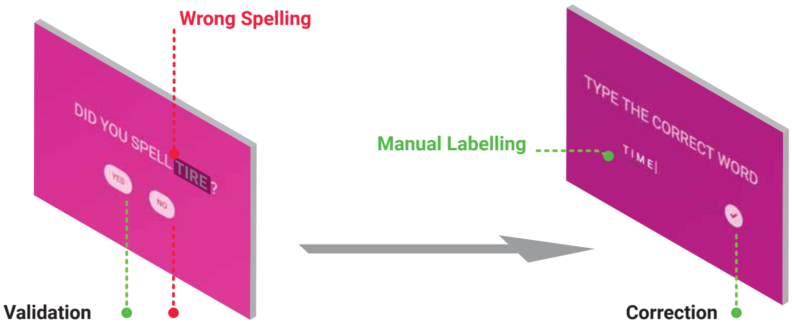


Figure 48: Two screenshots of the UI used for RSVP. Left. The predictor returns a misspelled word TIRE and the UI prompts the user for correctness. The user clicks No. Right. The user types the correct word TIME and submit the answer. The word is then used as a label for each datapoint in a character session of the dataset. Each point indexed as flashing a row/col containing the correct character is labelled as a target marker and others as non-target. The post-labelled dataset is then compiled with the existing dataset for continuous training.

One can observe over time that given the relatively low amount of data, selected pipelines grow fast in classification accuracy and reach a peak after 5 recording sessions. The additional channel on POz for the *Muse2+* acquisition configuration brings a significant increase of accuracy since adding more relevant data to the classification of the ERP wave and shows that *vectorizers + logistic regression* or *regular linear discriminant analysis* remain the best pipelines after the peak around *0.8* of accuracy. However, a completely different behaviour of classification over time occurs for the *OpenBCI* configuration. As this dataset contains more channels spreaded over the scalp, even though at a lower temporal resolution , it necessarily contains more data points and more variance to process for the classification. The difference in performances for the pipelines become then more important as their capacity to robustly handle such features is revealed in the plot. A significant peak already above the one observed with the 2 previous configurations reaches *0.9* approximately even before 5 recording sessions and shows that the pipeline with *ERP covariance matrices and projection on the tangent space* becomes the most accurate with the highest score very soon and remain above *0.8* even after 20 recordings.

Throughout this experiment, the methods of acquisition, pre-processing and classification of ERP have been devised with a minimal and convenient configuration for later applicative

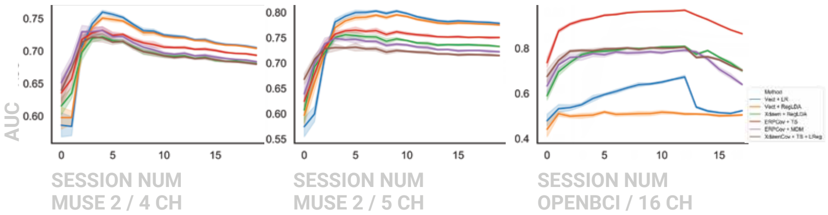


Figure 49: Evolution of the predictors accuracy by cross-validation with AUC metrics. Accuracies generally increase fast and reach a significant peak after 5 recording sessions to later slowly decrease and start to stabilise. A significant difference in predictors performances occurs between the two different acquisition configurations as they reflect embedded features.

purposes and take into consideration the challenging features that both data and applicative purposes might carry. Presentation and tokenisation of stimuli methods have also been described and generalised to be re-employed in further experiments. The use of a minimum configuration of 16 channels Openbci at proposed placements will also be maintained. More user-based adaptive processes could be applied such as parameter optimisation to increase classification accuracy, channel selection or time sample reduction to decrease the amount of datapoints, processing speed and variance. More sophisticated methods could also be taken into consideration to increase the learning of classifier across modalities (multi users, multi-sessions, multi-experiments) by applying transfer learning methods such as in (Coelho Rodrigues, Jutten, and Congedo, 2018).

3.2.2 *Neural Correlates of Design Beliefs*

Next page: Developments from the P300 BCI speller to a shape generator.

Question

Well known ERP from neuropsychology (Kutas, Kiang, and Sweeney, 2012) are widely studied and documented for reproducibility and can serve the role of evaluating acquisition, preprocessing and classification methods. New applications seeking to involve known paradigms necessarily involves that new experiments need to be designed with these precedents in mind in order to compare meaningful results. In order to dissociate the question of acquiring, preprocessing and successfully decoding neural correlates of cognitive processes from their applications for CAAD purposes, one should refer to current EEG signal challenges and transferability of learned patterns across modalities (Lotte, Bougrain, Cichocki, *et al.*, 2018). While state-of-the-art research in cognitive science is actively dealing with that matter (Coelho Rodrigues, Jutten, and Congedo, 2018; Tuleuov and Abibullaev, 2019), the present research focuses on the application of such potentials for better generalisations in future technologies for design and architecture. It engages with adapting known and generalised methods of acquisition, preprocessing, presentation, classification and exploitation from a P300 Visual Speller [8], for visual environments of increasing richness in information as commonly found in CAAD modeling interfaces (see Figure 50). It is known that, based on informational *Bayesian* models (Bayes and Price, 1763; Pierce, 1980), visual discrimination may occur in complex visual environments and their relevance for decision making rely on the degree of visual experience an individual may hold to construct prior beliefs upon which to infer (Goldstein and Learning (Firm), 2007; Lindsay, 1977). We will make use of previously built generalised techniques and trained models on a singular individual EEG signals and observe the robustness of advanced classification models to initiate the development of presentation and classification techniques for enriched visual environments by developping an iterative and generative design process of *growing shapes*. What is of interest is to observe if visual ERP as correlates of visual discrimination can hold in structurally similar but semantically different experiments and support ***the discrimination of meaningful design solutions***. Following bayesian terms, we will * coin such event a *Design Belief* and elaborate ***a method to explore and exploit these features decoded from human visual cognition***. *

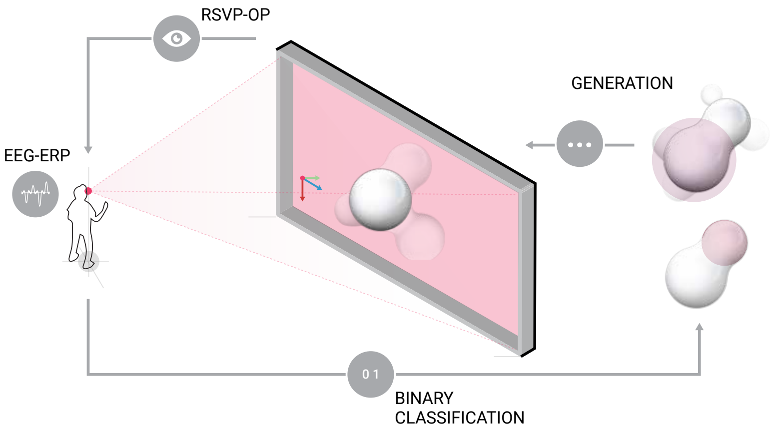


Figure 50: General Diagram of the closed-loop visual BCI generating tokens iteratively to be presented through a RSVP-OP paradigm in order to decode ERP features from EEG signals. They are later classified for identified targets to form the new seed for the next iteration of tokens.

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[8] see 3.2.1.

Tokens

The adapted visual stimuli use *3D metaballs* rendered by a marching cubes algorithm (Blinn, 1982; Lorensen and Cline, 1987) in order to provide a generic and smooth visual flow in the continuous variation and presentation of generated shapes by the rendering of implicit functions of isosurface. Each flashing epoch, previously showing a row or a column in the reference case of the visual speller, is replaced by the uniform random position of a new metaball instance in spherical coordinates (see Figure 51). We can consider α and β as the two rotation angles moving a point on a sphere of radius p (Equation (7), Equation (8)) *generated to give xyz coordinate* (Equation (9), Equation (10), Equation (11)).

$$\alpha = 2 * RandU(0, 2\pi) \tag{7}$$

$$\beta = \arccos RandU(-1, 1) \tag{8}$$

$$x = p * \sin\beta * \cos\alpha \tag{9}$$

$$y = p * \sin\beta * \sin\alpha \tag{10}$$

$$z = p * \cos\beta \tag{11}$$

The center of the spherical coordinates being either the origin of the rendered scene, or the center of one of the generated metaballs, if at least two already exist. In the case of none existing yet, a first instance will be placed at the origin for a second one to be generated from. Once the scene contains at least two instances of a metaball, the center point to generate a new one will be selected in a similar random fashion and produce the previously described relative coordinates for the new instance to be added for the rendering of the isosurface (Figure 52).

As a result, each new metaball instance P is parametrised with its coordinates xyz, and two parameters of field strength St and substract Su related to the isosurface calculations. Ideally, the radius R of the sphere to be rendered as a metaball is $R = \sqrt{\frac{St}{Su}}$, such that an instance can be parametrized as $P : (Px, Py, Pz, Pst, Psu)$and for an entire token T constituted of nP such that $T : [(P_0x, P_0y, P_0z, P_0st, P_0su), ..., (P_{n-1}x, P_{n-1}y, P_{n-1}z, P_{n-1}st, P_{n-1}su)]$. Eventually the final distance added to the coordinates of a new instance from the center of a previous one is equal to the radius of the later and the new resulting radius R. Each token can possibly have different distances between connected metaball and each metaball can possibly have different radii (Figure 53). We will consider these two configurations as two distinct classes *C1* (same distances and radiis) and *C2* (random distances and radii).

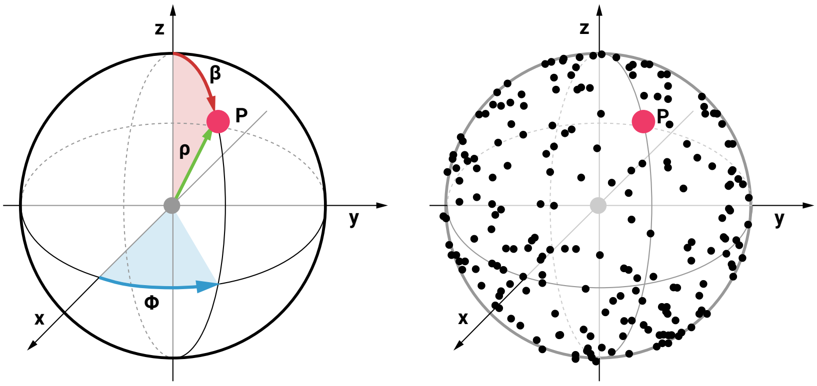

Figure 51: Random uniform spherical distribution of solutions for new possible coordinates of a metaball instance being later presented as a new stimulus. From a given center point O of a sphere of radius p, one generates the new coordinates x, y, z, of a point P and relative to O

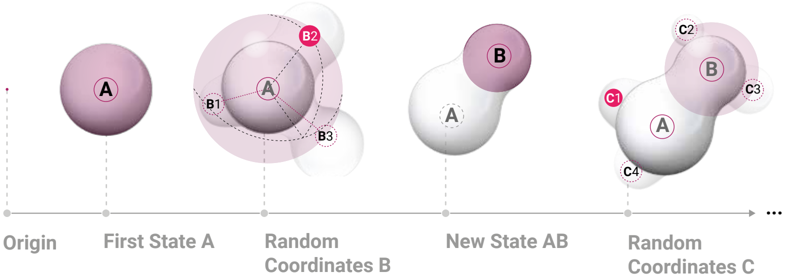

Figure 52: Sequence for updating the rendered isosurface. From Left to Right. A first instance is placed at the origin of the scene: First state A. New coordinates (ie. B1, B2, B3, . . . , as examples of possible generations) are generated, given the center of A and its radius: Random coordinates B. From B2, a new instance B is added to the scene: New state AB. Similalrly, new coordinates are generated (ie. C1, C2, C3, C4, . . . , as examples) from a randomly selected preexisting instance (A or B): Random coordinates C.

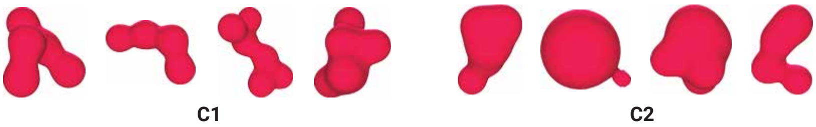

Figure 53: Left: class C1 samples with same radii and distances. Right: class C2 samples with random radii and distances.

In addition, Three main kind of shaders are applied to each tokens: *S1* - a plain white shader with no depth or shadow, *S2* - a *Phong* material shader with specularity and reflectance, *S3* - a black and white dot-patterned shader with no depth or shadow but applied on the uv coordinates of the shape (Figure 54). These three shaders allow for three different kinds of visual distinction of the complex geometry, depth, silhouette and curvature being rendered. They all relate to a certain kind of basic information sent to the visual system for early processing and known as *information of shape from texture and motion* (Palmer, 1999; Stone, 2012). The three applied shaders will be considered as three unrelated categories *Q1*, *Q2*, *Q3* for comparison of results, as providing different degrees of shape information.

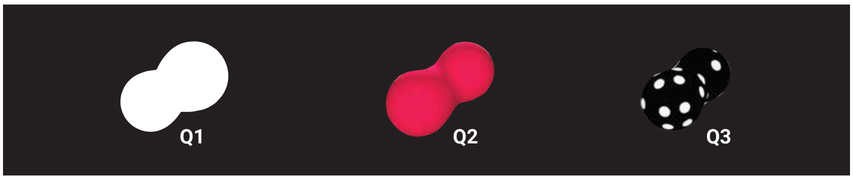

Figure 54: Rendering of the three distinct shaders as visual categories. A black background is used during the recording sessions.

Presentation

From the previous study of visual spelling with an ERP-BCI[9], the *Rapid Serial Visual Presentation* of the *Oddball Paradigm* Task (RSVP-OP) is preserved with a similar time and tokenization structure. Each presentation contains a sequence of 12 tokens shuffled and shown 15 times so that each token would be viewed 15 times in a random order of appearance. An initial period, to ease-in the user's attention into the visual scene and show how the tokenization will be presented, is set to 2.5 seconds. Similarly, a minimum of 2.5 seconds of a break period is set between presentation periods to avoid rapid fatigue and disengagement. Since the temporal method used for classification is offline learning and the next presentation period is dependent to the processing and the returned discriminated token by a pre-trained classifier (ie. a new tokenization can happen only if there is a new state returned), the break period is also extended until a value is returned (ie. the index of one of the presented tokens or none in case of no discrimination found). Each token is presented on screen for a duration of 0.1 seconds and followed by a blank screen for a duration of 0.075 seconds while the standard refresh rate of the visual presentation is approximately 60Hz. Each recording session has been kept under a maximum time of 18 seconds (excluding the break periods) and 6 discriminated tokens forming the overall shape. The main adaptation from the generalized RSVP-OP consists in augmenting its temporal structure (Figure 55).

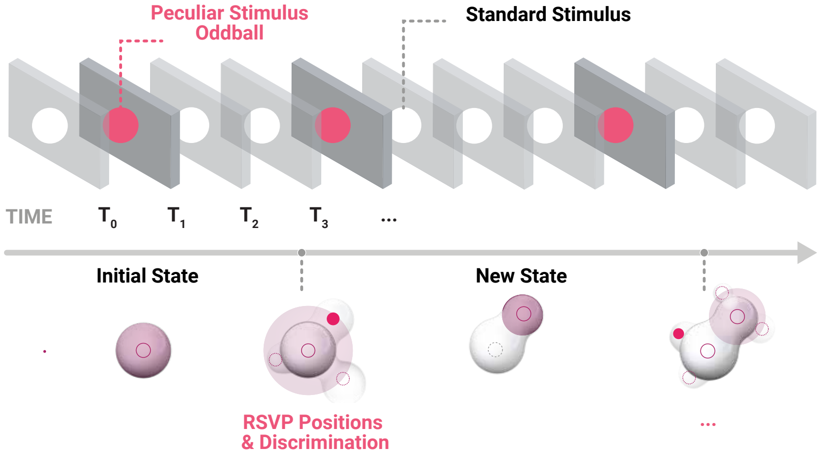

FIGURE 55: Adaptation of the typical RSVP-OP task. Between stimulus presentation, another presentation period is introduced to show the new state of the overall shape formed by discriminated tokens and from which new tokens will be generated for stimulus presentation. This new period also plays the role of helping to reduce prolonged cognitive workload and await for discrimination and generation of new stimulus for the next RSVP-OP.

While the RSVP-OP occurs, data is acquired accordingly. And while the data is being processed during break periods, the current state of the shape is kept visible until a new value is returned and the new state of the shape is shown for a a second before starting the new RSVP-OP and in order to generate the new tokens. Additionally, and since the complexity of visual scenes presented is more important than in the case of a word speller, the RSVP is adapted at every token flashed so that its silhouette appearing on screen is maximized. This effect is achieved by measuring the angle α between: 1 - the line a formed the centroid C_s of the shape and the center C_t of the presented token; 2 - the *X-axis* b of the scene always horizontal

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[9] See 3.2.1

and parallel to the camera *X-axis*. A rotation is then applied to the shape so that $\alpha_{ab} = 0\,\text{deg}$ as in Figure 56.

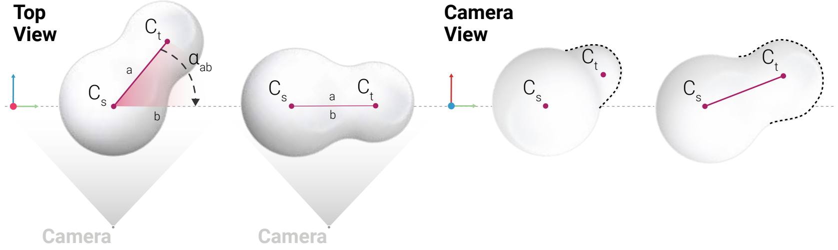

FIGURE 56: Rotation applied to the shape around its X-axis during each token presentation of the RSVP-OP period in order to increase each presented token's visibility. Cs is the centroid of the shape in its current state and Ct is the centroid of the token being presented as a stimuli. Both are forming a line a from which is measured its angle alpha(ab) formed with a vector parallel to the camera's Y-axis and passing by Cs, noted b. The rotation is applied on the whole shape (including the token) around the vector parallel to the camera's X-axis and passing by Cs, so that alpha(ab)=0deg.

This method provides a new view angle of the shape at each token presentation and allow for novel information of the overall shape from motion and texture (Palmer, 1999; Stone, 2012), while the visibility of the token is emphasized to ease the discrimination. Additionally, a random rotation is constantly applied during break periods to show more information of the overall shape before presentation. A recentering and rescaling of the camera occurs also before every new presentation to ensure that the centroid C_s of the shape remains at the center of the scene and the whole shape is contained and visible in the rendered scene.

Acquisition

Following considerations and results of the first experiment, The EEG data is acquired through a *Lab Streaming Layer* protocol (LSL[10]), synchronized, and by a 16 channels *OpenBCI*[11] (*Daisy* + *Cyton* configuration) at a sampling frequency of 125 Hz with electrodes placement at FC5, FC6, C3, Cz, C4, CP1, CP2, P3, Pz, P4, PO3, POz, PO4, O1, O2 and Oz positions of the *Modified Combinatorial Nomenclature* (MCN) of the *International 1020* placement (Sharbrough *et al.*, 1991). Signals are digitized at their device's sampling frequency and then filtered with an eighth-order bandpass filter with low and high cut- off frequencies of 0.1 and 20 Hz, to finally build epochs from -0.100 to 0.700 s onset visual stimulus and downsample each signal to the high pass limit since most ERP components can be found below 20 Hz. (Luck, 2014). No particular artifact rejection method is applied except for amplitudes superior at 75 microvolts to reject outliers from muscular movements. This allows for a minimisation of datapoints to process within the range of ERP detection.

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[10] See link

[11] link

Discrimination

For similar reasons explained in previous experiments [12] concerning challenging EEG signals features for stable classification (mainly signal-to-noise ratio and non-stationarity), the capacity for a given classifier to learn across different modes (different sessions, experiments and users) without calibration is a question of research on *transfer learning* itself (Lotte, Bougrain, Cichocki, *et al.*, 2018) and can be approched by *information geometry* (Coelho Rodrigues, Jutten, and Congedo, 2018) or *deep learning* (Tuleuov and Abibullaev, 2019) methods. Given the low amount of data and the user-based approach of the experiment, information geometry classifiers have been chosen and trained for a single person on multiple recording sessions of a p300 word speller [13], so that the assumed learning across-modalities would concern only the cross-experiments mode (ie. from *spelling words* to *growing shapes*). The pre-trained classifier is a *riemannian* classification pipeline constituted of *ERP covariance matrices* and *projection on the tangent space* (Congedo, Barachant, and Bhatia, 2017; Barachant and Congedo, 2014; Barachant, 2019a) with an AUC accuracy of 0.975 after 12 training sessions. Given previously mentionned EEG features and an increasing variance in the data when applying new experiments, the robustness of such method is evaluated by observing the difference of averaged discriminated samples recorded during the new experiment (Figure 57). Though observed on less data amounts than for training, one can see that despite changes in the morphologies of signals and presence of noise, the classification accuracy across experiments for a single user can be maintained to a certain degree, although it may not provide for a continuous and fully robust adaptive classification across all mentioned modalities.

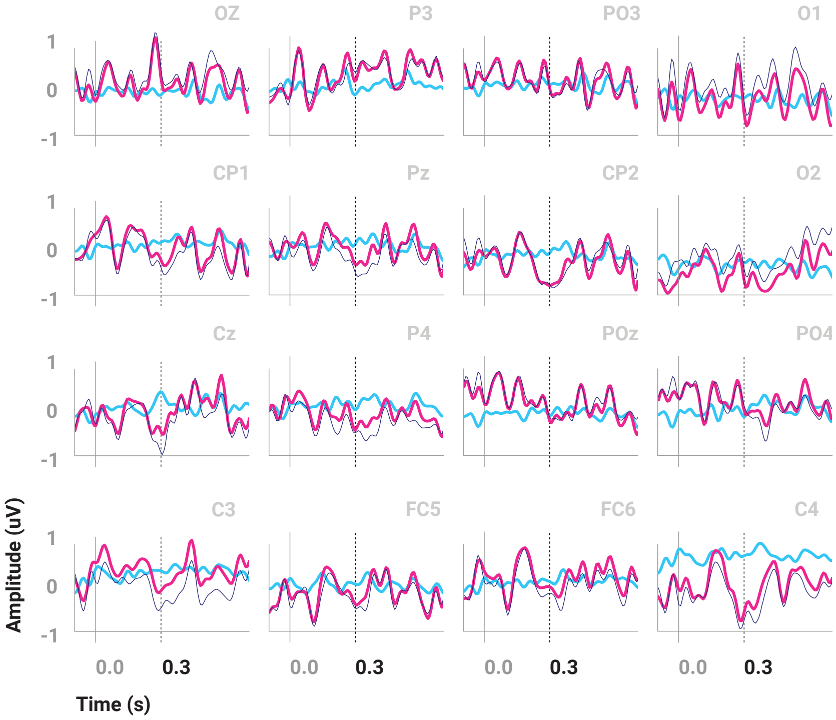

FIGURE 57: ERP binary conditions of discriminated data with the shape generation experiment. Red plots show positive Target. Blue plots show negative ones. A difference waveform is plotted in dark blue.

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[12] See 3.2.2.

[13] See 3.2.1 and 3.2.1.

Generation

During the developped RSVP-OP sessions and parameters, two types of data are recorded into a user's database : 1 - aggregated and processed timeseries used as input for the classifying pipeline, segmented by presentation period (ie. one for each discriminated token). 2 - generated shapes directories, containing their *Q-C* shape labels (see *Tokens*), the mesh file and its associated material (Figure 58) computed by the programmed shaders (in **.obj* and **.mtl* formats), and a **.json* data file containing all parameters used to procedurally generate the given shape (**??**). The later is used for further understanding on the extent of the produced solution space and its features. Eventually, a similar method can be used to proceed from an *inverse modeling* fashion to generate such shapes, given an adequate artificial generator.

Figure 58: Grid of all the generated shapes by Q-C order. Original shaders have been replaced by colors for better overall visualization. Bottom to top, Left to Right : Q1 (pink) with 50 C1 shapes and 50 C2 shapes; similarly followed by Q2 (black) and Q3 (grey).

.	**Px**	**Py**	**Pz**	**Pst**	**Psu**
0	0.5	0.5	0.5	0.61	15.6204993518133
1	0.556925825892438	0.495865511380644	0.645404113938775	0.61	15.6204993518133
2	0.454769577708112	0.495483133279051	0.763573292424071	0.61	15.6204993518133
3	0.511977763440335	0.644353703985817	0.663595549798839	0.61	15.6204993518133
4	0.570358966169001	0.6833208678336600	0.8031419410442230	0.61	15.6204993518133
5	0.538020627839912	0.5735796581797780	0.9094955906187250	0.61	15.6204993518133

Table 2: A sample *.json file containing parameters Px, Py, Pz, Pst and Psu for each instance (0 to 5) necessary to procedurally generate its associated shape.

Results

From all data files of *Q-C* shapes generated, a dimensionality reduction is applied from the initial 36 shape dimensions (6 instances X 6 params) to a 2D mapping using T-SNE (Maaten and Hinton, 2008) and UMAP (McInnes and Healy, 2018) to evaluate the topology of the aggregated data and account for possible manifolds. In order to observe a differentiation between possibly random shape generations and otherwise meaningful ones, they are compared with randomly generated data using similar procedural methods and parameters for both *C1* and *C2* classes (Figure 59).

Both T-SNE and UMAP methods show similar clusters and suggest that discriminated data correlate only in part with random data points. As some clusters appear outside the random ones in more compact topologies, they suggest a meaningful convergence for some generated shapes. Since visual ERP is clearly correlated with visual attention (Kutas, Kiang, and Sweeney, 2012), another index of engagement is added to help in visualising the relation of engagement with discriminated shapes (Figure 60). The index used for this is a commonly used $\beta/(\alpha+\theta)$ index (Pope, Bogart, and Bartolome, 1995), where the mean relative bandpower of θ : 4–8Hz, α : 8–12Hz and β : 12–30Hz frequency bands are computed for each aggregated timeseries of a shape. Since this index is computed on pre-processed EEG data which has been filtered and resampled to a maximum of 20 Hz, the β band is being cut by approx. 0.55, a naive factor k is applied on the mean value of the β band such that $k = 0.55$ and: $index = \frac{\beta + k\beta}{\alpha+\theta}$.

The mapping of engagement index on clustered discriminated data shows peaks of engagement both in specific clusters and random ones. It also shows that very few low peaks are present on the specific clusters. One can interpret such topology by summing that some meaningful clusters are formed but some data points outside of them might also be of interest and that such index would be helpful to adjust their meaningfulness.

The robustness of generalising the acquisition and classification methods across experiments for a single user can be maintained to some extent and would greatly benefit from further adaptive research in stimulus presentation and transfer learning. We have engaged into modifying typical RSVP methods to the end of easing the rendering of complexified stimulus presentations towards design and architectural modeling purposes. Through the accumulation of generated shapes, we have shown that some meaningful clusters emerge to form what we

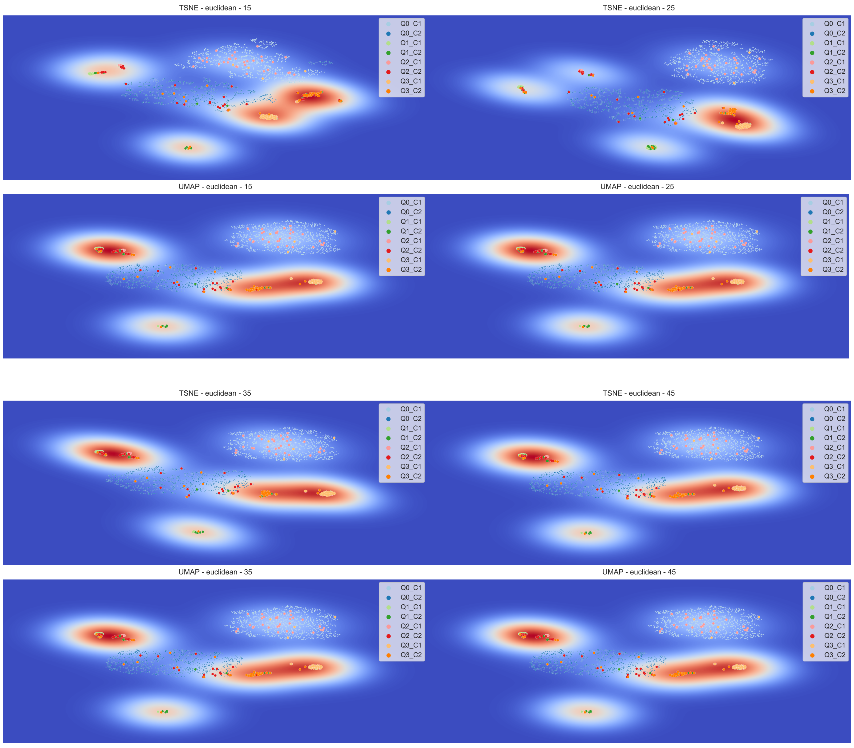


Figure 59: T-SNE and UMAP 2D dimension reduction of the generated data. Both are run with several perplexity/proximity parameters (15 to 45 with step of 10) to observe the persistence of clusters topology across global/local structures. The map contains 20000 random data points and 300 discriminated ones. A gradient plot in the background shows the proximity of discriminated data points in clusters. Label Q0 is a random generation with C1 and C2 parameters found in Q1, Q2 and Q3. Row 1-2: T-SNE (Top) and UMAP (Bottom) clusters with perplexity/proximity parameters 15 (Left) and 25 (Right). Row 3-4: T-SNE (Top) and UMAP (Bottom) clusters with perplexity/proximity parameters 35 (Left) and 45 (Right).

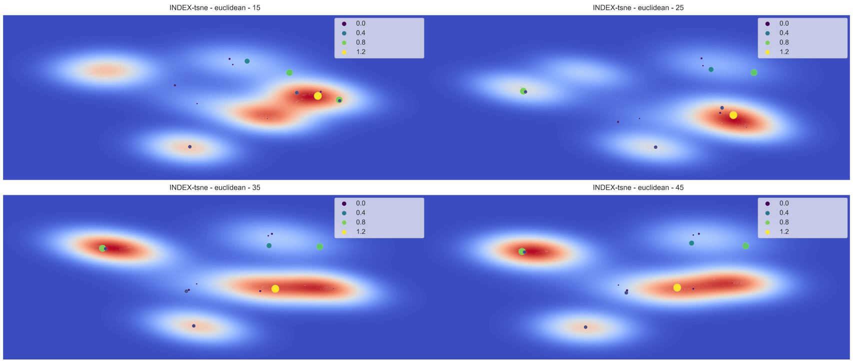


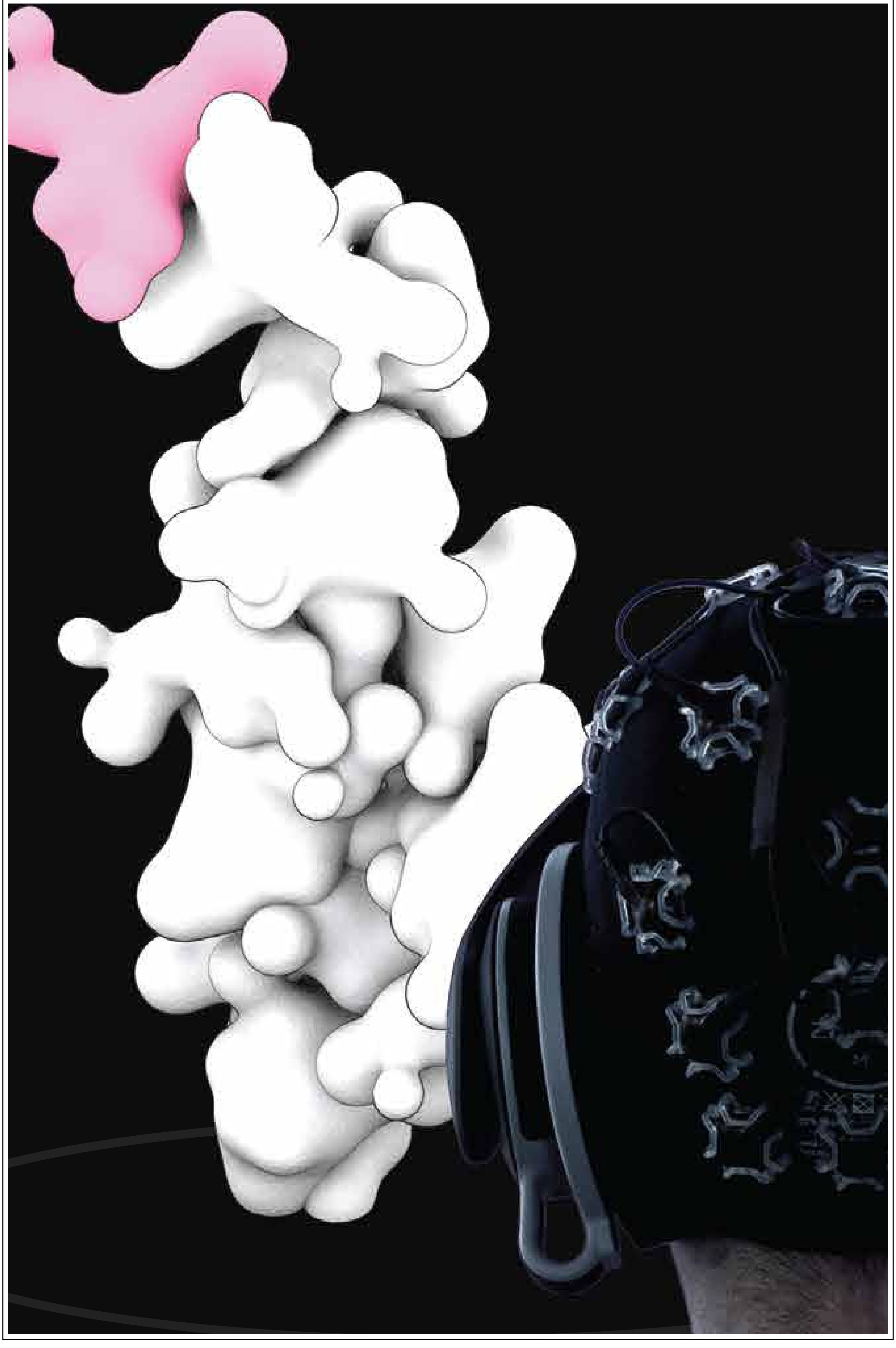
Figure 60: Mapping of the Engagement index for each discriminated data points already projected on the 2-dimensional plane with T-SNE. From Left to Right and Top to Bottom: plot with perplexity parameter of 15,25,35 and 45.

can now call a ***Design Belief*** in the way they aggregate around regions in the latent space for peculiar design solutions and parameter ranges over time and based on typical informational bayesian prior beliefs. *

In addition, engagement indices of visual attention such as the one used in the present experiment can be purposed to value and ponder both formed design beliefs and episodic discrimination outside such regions but with high engagement index in order to notice other possible regions of interest. This should allow ***to further devise for a method to generate design solutions based on the discrimination of such design belief together with an exploitation/exploration ratio of the design space, in order to maintain variance over time in the*** * ***generation of design solutions***. Further experiments will develop this combined discriminative/generative method together with a better granularity of ERP classifications and stimulus presentations moving from the generation of shapes to the spatial articulation of parts for architectural modeling implementations.

3.2.3 *Aggregating Parts With Design Beliefs*

Next page: Protypical modeling by aggregating parts with the developed BCI.



Question

We have previously seen that standard methods and paradigms used in visual spellers may be transformed to explore the discrimination and generation of iterative design solutions representing increased visual complexity. The emergence of clustered results over time suggested that beliefs towards particular regions of the latent space could be captured and their timely modulation observed[14]. With that in mind, further techniques must be sought to address the full complexity of tasks in CAAD, and use such design beliefs as a visual articulation strategy. How to deal with parts is a fundamental question that lies at the core of the architectural principles of architectonics[15], and therefore constitutes a great case study for that matter when intending to articulate parts together in significant relation to the particular concept of an architectural element (eg. aggregating parts to form a column). When dealing with visual stimulations of increased complexity, the correlation with specific neural phenomena might evolve accordingly to significant degrees of uncertainty. Logical discrimination is generally framed by 4 distinct classification outcomes labeling an instance whether or not to be positively mapped to a label (Fawcett, 2006). While it is widely used in BCI classification methods, in correlation with labeled stimuli under attention (eg. BCI speller), it becomes insufficient or even inappropriate when lacking labels and elicitations come from complex and ambiguous inputs. Classes may become unbalanced, and labels absent from the design of the task (Tibon and Levy, 2015; Huebner *et al.*, 2018). There should be, however, a minimal amount of found classes involved in particular sensory discrimination under a logical framework, once provided with a standardized presentation of these stimuli. Their cardinality should remain independent from the informational complexity of the stimulus but should be factored by cognitive parameters linked to attention such as stimulus probability (Rosenfeld *et al.*, 2005), mental workload (Appriou, Cichocki, and Lotte, 2020), and the user's experience in practicing with BCI (Vidaurre and Blankertz, 2010). Moreover, the separation of these classes under uncertainty should allow for a generalization inter-session and inter-subject given the development of adequate adaptive learning methods on a prolonged usage basis (Roc *et al.*, 2020). However, in the case of CAAD where such application is sought to replace obstrusive design rules, the lack of labels and description of the task remain a challenge of multiclass classification and unsupervised learning. A discriminator must be trained to learn unlabelled classes in order to make use of the formation of design beliefs and a generator must learn to modulate its solution space towards found labels. This experiment focuses on adapting presentation and generative aspects of the interactive loop in order to practically find ways to model with neural potentials and identify issues that need further research Figure 61).

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[14] See 3.2.1 and 3.2.2.

[15] See the previous chapters and more synthetically *Modeling With Neural Potentials*

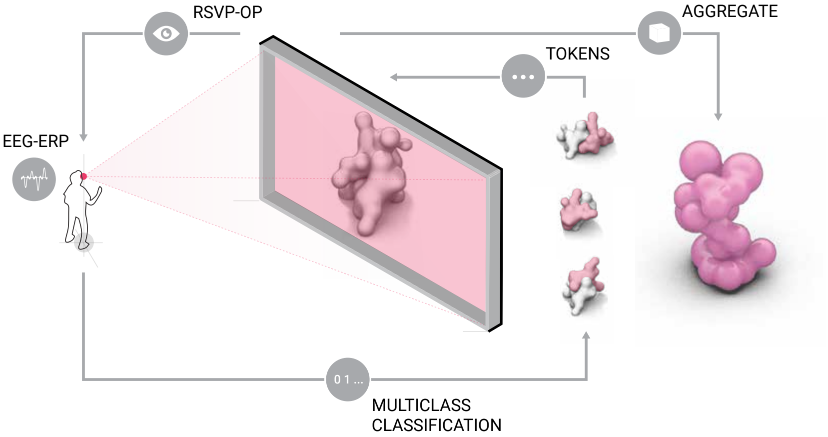

Figure 61: General Diagram of the closed-loop visual BCI. It follows the same principle than previous experiments and introduces multiclass classification for the generation of aggregates of parts over time.

Tokens

The tokens selected as fixed geometries and graphic properties are provided from a previous experiment [16] as sets of non-trivial and non-convex geometries with no visual explicit cue of potential connectivity between each other. The previously used graphic properties remain similarly purposed to provide a diverse range of shape information from shading, texture and motion (Palmer, 1999; Stone, 2012). In order to provide for a wider range of possible parts as tokens, their geometry is dissociated from their other features and recombined as per user explicit selection through a user interface. Followingly, a given geometry from a set with a given particular shader can be recombined with a different one procedurally on demand. This serves as a prototypical interface to progressively draw a user's attention towards the task, while explicitly adjusting per user the amount of features involved in the generative process. Every part picked for tokenisation is done so from a random uniform selection of the previously made available ones, depending on only two sets of common properties : *same part, various part* and *all materials, any materials*. Meaning that 1 - a picked part will be the same for the whole aggregate, or 2 - a new part will be picked every time, 1a/2a - with a specific material, or 1b/2b - a randomly chosen one. While not taking part in the tokenisation but only in later steps of discrimination, a minimal visuo-semantic cue is given for the modeling task to be accomplished in relation to the category (eg. column, dome, wall,. . .) it should refer to (see Figure 62). As a whole, this minimal UI forms a sentence articulated by both the task (action) to perform, and the non-constrained parameters (unitisation and material) involved in the tokenisation. The procedure of automated tokenisation is made through an external CAD API[17]. The scene used to render the solutions is a physics engine simulation in the software *Blender*[18] allowing for collision detections, forces and physics properties of materials which play a role in the placement of a part. It is originally based on the *Bullet* physics engine[19] for collision detection and multi-physics simulation.

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[16] See 3.2.2.
[17] link
[18] link
[19] link

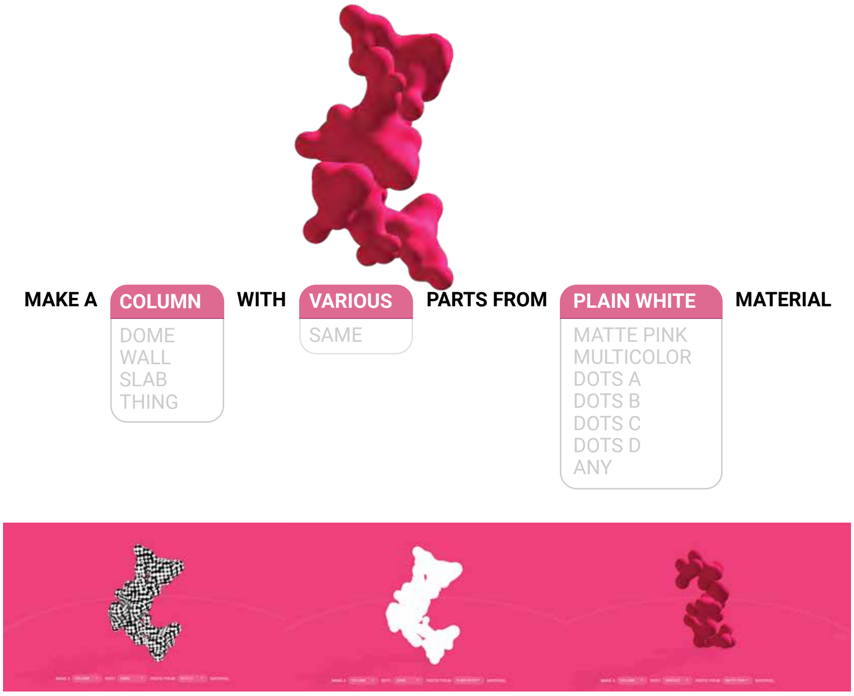
MAKE A COLUMN WITH VARIOUS PARTS FROM PLAIN WHITE MATERIAL

Figure 62: Top: Initialisation interface for the tokens generation and forming the minimal semantic cue. The cue is formed by three parameters of category (column, dome, wall, slab, thing), part unitisation (same part, various parts), and parts properties (ie. Material). Bottom: Screenshot of different tokenisation settings as viewed from the UI.

As shown in Figure 63, Given a ground plane $(G)_z = 0$, a part B to be instantiated, randomly picked as $B = RandU(S_B)$ within the set S_B of all existing parts with pre-selected properties M (material) such as $S_B = S : U \cap S : M$, and an updated set $S_A$of pre-existing $n$parts in the scene $S_A = \{A_0, ..., A_n\}$, the part A from which a new one will be instantiated is picked as $A = RandU(S_A)$. The shortest distance between the respective bounding spheres of A and B being the sum of their radius $\overline{AB} = R_A + R_B$. The orientation of the starting position for B is picked randomly, hemispherically (z positive above G) around A if it lays on the ground and spherically if not, such as Equation (12) and which finally allows for giving cartesian coordinates as Equation (13) and euler rotation to B as Equation (14):

$$(\phi, \beta) = \begin{cases} (RandU(0, 2\pi), \arccos(RandU(-1, 1))) : A \cap G = \\ (RandU(0, 2\pi), \arccos(RandU(0, 1))) : A \cap G \neq \end{cases} \tag{12}$$

$$B_{x,y,z} = \begin{cases} x = \overline{AB} * \sin\phi * \cos\beta \\ y = \overline{AB} * \sin\phi * \sin\beta \\ z = \overline{AB} * \cos\phi \end{cases} \tag{13}$$

$$B_{\phi,\beta,\alpha} = RandU(0, 2\pi) \tag{14}$$

The latent representation of one token within an aggregate is therefore a vector$B$of 8 dimensions, such as: $B \rightarrow (S_0B, B_{x,y,z}, B_{\phi,\beta,\alpha}, S_MB)$ where S_0B is the index of the part's geometry file, $B_{x,y,z}$ the cartesian coordinates to its centre of gravity, $B_{\phi,\beta,\alpha}$ its euler rotations around this centre, and $S_M B$ its material properties. Once the token pre-positioned, the physics simulation is launched. In the case of the very first part with no pre-existing ones in the scene, it is positioned on the Z-axis at twice the diameter of its bounding sphere and randomly rotated as previously described. A new part B will then be subject to an attraction force from its 3 closest neighbours updated at each simulation step and a general gravity force. A collision detection check with all parts and the ground is performed under the physics simulation, while a proximity optimisation between B and the closest part is ran. Finally, once a certain stability is found, the simulation stops, freezes the parts parameters and exports it for tokenisation. The overall parameters and functions are described and wrapped within an expensive objective function to minimise. Its optimisation is ran as a blackbox method (Knysh and Korkolis, 2016) and implemented in *Python* with the running API[20]. A cost effective solution to avoid any optimisation step could be developed to pre-specify rules of aggregations based on topological analysis and heuristic methods. However, since the goal of this research leans towards the minimisation of any predefined generative grammar, such optimisation method is used instead to maintain variance and its caveats (time, computing power) will be overcome at a later stage during generation. As such, this developed method for general tokenisation and data generation allows for simplified case-studies of self-interlocking, non-standard, parts to aggregate, as well as the physical prototyping of such aggregates with dry assembly and disassembly by implicitly embedding into each tokens the possibility for physical inclusion and exclusion of the parts, in their sequential order of appearance in the aggregate.

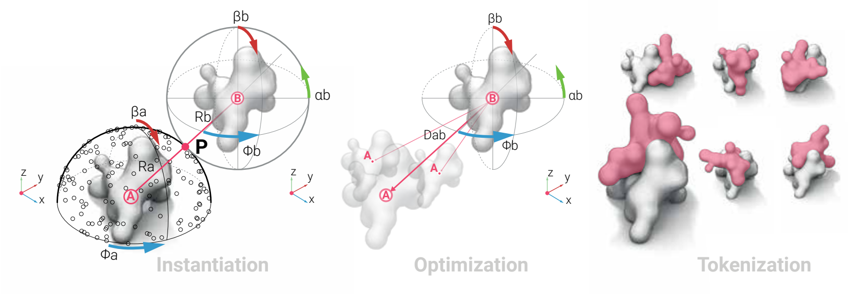

Figure 63: Generalised steps for tokenisation. Left to Right : Random Instantiation of parts, with parametrised position and rotation - Parameter Optimisation by minimisation of mean distance and collisions with the three closest pre-instantiated parts - Parameters freezing and tokens presentation.

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[20] link

Presentation

Although the rendering of tokens and the aggregate scene for visual presentation is set in two variants for the successive steps of training a discriminant classifier, and using it for generative purposes, the visual presentation structure remains the same. As in previous experiments [21], a RSVP-OP sequence is used with 12 tokens shuffled and presented 15 times with initial periods and breaks of 2.5 seconds. Token presentation periods last for 100ms and blank periods for 75ms, with a screen refresh rate of approximately 60Hz.

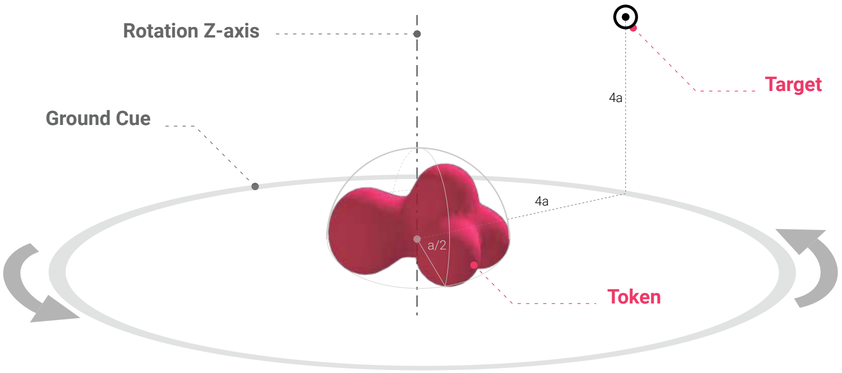

FIGURE 64: The initial RSVP scene for the training task. A target is placed above the ground, cued by a light grey circle. The camera is tilted above the scene and towards the origin of the scene. A visual target is placed above the ground at 4 times the diameter of the initial token positioned at the origin of the scene. The initial token is having its position and rotation parameters simulated after being picked randomly from the set of available tokens and according to the physics simulation to pre-condition the presented visual information with implicit stability of the token. The entire scene is subject to a continuous rotation around its Z-axis during the whole RSVP session.

The training task consists on reaching an explicit visual target by discriminating tokens which would appear the closest (See Figure 64). A 3d scene is rendered with already a randomly picked token from available ones and placed at the centre of the scene, on the ground. A few minimal cues are given as to provide for information on ground limits and visual area of focus by a projected light circle on the ground. In order to provide for greater variance of visual information during the presentation tasks, a continuous vertical rotation occurs around the z-axis of the scene. Both placement of the initial token and the following ones used during the RSVP are picked and placed generatively and asynchronously in advance of the presentation and as described above in Tokens. In order to account for potential various ranges of ERP amplitudes and latencies in correlation with the complexity of the visual task and its related cognitive loads (Donchin, Kubovy, *et al.*, 1973; Hagen *et al.*, 2006), a group of presentations for controlled variance is designed for the overall session and should allow for a better generally learned discrimination. The tokens presentation session is then divided in 7 steps as follows: the first six steps consist in presenting random sets of tokens of increasing amounts (from 1 to 6 tokens at a time respectively for each steps), while the last one consists in presenting random sets of random amounts of tokens between 1 and 6, different from the previous sets (see Figure 65).

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[21] See 3.2.1 and 3.2.2.

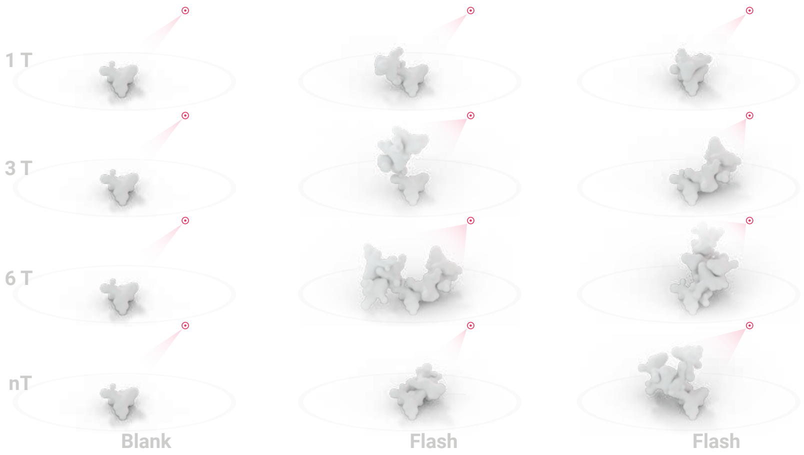

FIGURE 65: Samples of presentation of the 7 steps used during the training sessions. Each step sample is represented here by row, for the presentation of 1 token at a time (1T), 3 tokens (3T), 6 tokens (6T) or a random amount of tokens (nT). Blank periods are represented in the first column with the initial token picked randomly for each step (represented identical here for an easier comparative overview), followed by two samples of tokens presentation during flash periods. A pink gradient illustrates for each the designed variance in evaluating visually the proximity of the overall shape with the target (in pink). Tokens materials are not represented here for visual simplification.

Given the length of 12 tokens, each training session comprised of these 7 steps is having a total time T_S as Equation (15) and following previous equation[22]. Which gives here a session time of approx. 256 seconds, given eventual latencies, and a total of 1260 epochs for all presented tokens. Datasets aggregate per user each time a training session is being recorded and includes the material and unitisation parameters chosen by the user during the introductory UI (see Figure 66). The generating task employs a similar time structure but embeds a UI which allows the user to stop the session at any time, continue it later to iterate over an existing aggregate, or to redo the session from scratch. The amount of tokens is set to random between 1 and 6 for the entire session and is programmed as scalable parameter for future experiments where larger aggregates will become investigated. In order to provide a constant overview of the entire aggregate in the scene, the camera refocusses and fits the updated aggregate within its field of view. Further details will be presented hereafter[23].

$$T_s = 7 * (2.5_{sec} + (0.1_{sec} + 0.075_{sec}) * 12 * 15 + 2.5_{sec}) \tag{15}$$

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[22] See 3.2.1.

[23] See 3.2.3.

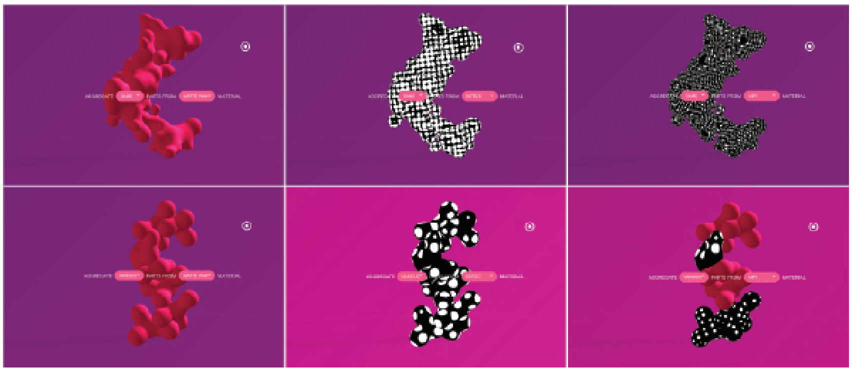

FIGURE 66: Introductory UI for the training task of reaching a visual target by discriminating the closest tokens. Unitisation (same part for all tokens or not) and material (a specific one for all tokens or not) parameters allow for a customisable variance of provided information from shape and texture.

Acquisition

Data acquisition was done similarly than previous experiments[24]. During training, a last preprocessing step is added to the segmentation by labelling epochs with binary values depending of the occurrence during a target flash/token or not due to the persistence of prior aggregates during inter stimulus intervals. All epochs can then be averaged and optionally plotted according to these conditions in order to allow for visualising whether or not the chosen acquisition method and device configuration permits the finding of ERP patterns exhibiting a clear separation between target and non-target epochs. Training datasets aggregate per individual user each time a training session is being recorded. For the given processed frequency (20Hz), channels (16), session time (256s) and presentation labels (target, non-target), each training session results in samples of 5120 datapoints of 17 dimensions. In addition, each flashed presentation containing a token is recorded with both the tokens parameters : $(B \rightarrow (S_0 B, B_{x,y,z}, B_{\phi,\beta,\alpha}, S_M B)$ for each B token being presented at once), relative distances to the visual target (D_0euclidean distance between target and the closest point on aggregate, and D_1euclidean distance between the visual target and the centroid of the entire aggregate), and the scene parameters (averaged rotation angle at presentation time). These particular data are used for training the discriminator in better assessing the correlation of the task with found neural responses.

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[24] See 3.2.1, and 3.2.2.

Discrimination

It is important to notice that an elicited discriminative neural phenomena such as an ERP does not necessarily implies the positive discrimination of an event during RSVP but can also be correlated with other psychological states such as *error recognition* (Falkenstein, Hoormann, *et al.*, 2000) or *novelty detection* (Barry, Steiner, and De Blasio, 2016). The phenomena associated with the recognition of an error is commonly noted as *Error-Related Potential* (ErrP) and can be comprised of all components of an ERP (Chavarriaga, Sobolewski, and Millán, 2014). Empirical evidences grow around the detection of ErrP and its correlation with erroneus BCI feedbacks (Chavarriaga, Sobolewski, and Millán, 2014; Falkenstein, 1990; Ferrez and del R Millan, 2008). The second phenomena associated with novel events, commonly noted as *Novelty P3* (nP3), is generally found when rare but peculiar stimuli occur out of context or target scope (Courchesne, Hillyard, and Galambos, 1975). It is highly correlated with the *Orienting Response* (Sokolov, 1963; Friedman, Cycowicz, and Gaeta, 2001), a shift of attention due to relevant environmental changes. Therefore the elicitation or not of an ERP by a target stimuli would not suffice to establish a proper classification solely through a binary approach, specially given the increased visual complexity of presented stimulus. As a target could be eliciting an ErrP instead, or a nP3 could be found elicited by a non-target stimuli. In order to rather address the larger spectrum of such responses to rich visual environments and be able to maintain an adequate range of discriminations, we propose to apply a four-class classification approach, comprised of the aforementioned three potential neural responses and for the visual discrimination of such stimulus: positive, novelty and error-related potentials. As the task designed for training session embeds the evaluation of the visual proximity of presented tokens with an explicit target, the four-class classification method will be represented by the explicit labelling of the user for each presented tokens after EEG data acquisition. Since asking a user, during stimulus presentation, to focus on multi-label discrimination simultaneously would require to maintain a significant cognitive load and training, the required visual discrimination solely focuses on the binary discrimination of the stimulus assessed to be the closest to the cued target. We therefore use explicit labelling immediately post stimulus presentation to provide non-target epochs with a wider spectrum of labels. A new UI will then appear to the user and show every flashed token presentations given recorded tokens and scene parameters. An explicit labelling field will accompany each one of them to correlate the targeted classification with explicit labels, and where an ErrP or irrelevant phenomena could be found when data labelled as *"BAD"* non-target epochs, a positive P300 when labelled as *"GOOD"* for *target epochs*, and a nP3 when labelled *"INTERESTING"* for *non-target ones*. Labelled ones as *"NOT INTERESTING"* should confirm True non-targets (see Figure 67).

The prior assumption is that such an explicit labelling for discriminatory classification would allow for both a better separation of classes over time, but also a better generalisation of trained discriminators when visual tasks will evolve. Explicit labelling and aggregation of training datasets over time should permit to improve the discriminator accuracy for an individual user while maintaining a wider range of variance in discriminated tokens. However, it is to be noted that such generalisation can only be found and confirmed in studies with extended populations. The variance of responses from an individual to another and from one session to another relates to topics of research previously mentioned regarding question of literacy and measures[25]. Nevertheless, this technique necessarily implies that found classes would constitute an unbalanced distribution over time but could start initially with a binary cluster from available samples, to progressively intend to separate classes in up to 4 clusters over the

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[25] See 3.1.2 and 3.1.5.

Figure 67: UI At the end of each recording session for training. Each presented token for each step is shown again in similar presentation parameters and as a grid synoptically to each tokens presentation step (last step of random tokens shown here). The user explicitly labels them with GOOD, BAD, INTERESTING, or NOT in regard to the visual task of assessing the tokens proximity with the target. The third label might imply that the presented token disatisfies the task but is in itself salient to the user. This explicit labelling translates in the recorded EEG data into the Labelling of ERPs to be found. Respectively P300, ErrP and nP3 for correlated synchronous token presentations.

cumulative course of training sessions.

Generation

The generation principle established for this research is an *iterative* one. Meaning that new tokens should be generated on the basis of existing priors. To that end, the generative process is to be understood as a *sequential* generation with unknown degrees of relations in regards to all previous indexes (ie. previously generated parts and presented as aggregate). The second generative principle concerns a certain amount of design assumptions in regard to an aggregate and its parts. We are calling these assumptions *Design Affordances* (DA) to underline their arbitrary rules in regards to what a particular CAD systems or a finite set of given parts may afford to perform, in an environment external to an individual's internal cognitive system, while being aggregated. Using such DA will allow us to unspecify any further design grammar in the way these parts should be articulated and provide a clear differentiation in what kind of features is initially learned by the generator from an original dataset, and what is being progressively learned from an active visual discrimination. As a starting point, an initial dataset of 10000 aggregates made of 100 parts picked randomly from a finite set, and 10000 aggregates of similar parts from the same set, is generated (see Figure 68) using the method described previously above in Tokens. The minimal DA embedded in the generation of this dataset is regarding physics collisions and has three simple conditions: a ground plane $(G)_z = 0$ which should not be traversed, a finite parametrisation of each part $B \rightarrow (S_0B, B_s, B_{x,y,z}, B_{\alpha,\beta,\gamma,\phi}, S_MB)$defining their material and geometric transformations within the aggregate, and a proximity/collision of new token parts against prior parts within the aggregate and which are solved within the simulation environment. In contrast with the precedent tokenisation method, the scale parameter $B_s$is reintroduced for each part (even though a constant) for further generalisation and the rotation parameters are converted to a quaternion $B_{\alpha,\beta,\gamma,\phi}$in reference to the CAD global coordinates system and its origin. Implicitly, the part index S_0Brepresents the part geometry which will be used for solving collisions but not exposed in the dataset (ie. only the part index will be exposed). Theoretically, every new token could be generated as previously but would take considerably more time and present no further capacity for adaptation with potentially newly incoming and unknown features, as well as for interactive modes.

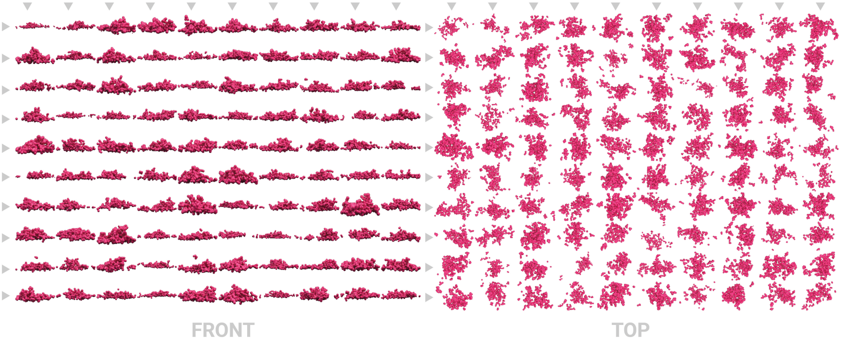


FIGURE 68: Samples of generated aggregates for the initial dataset. Left - Front view. Right - Top view.

Given the mentioned principles used for designing the dataset, its latent representation can be encoded for each generated aggregate with additional information: whether or not an aggregate is constituted of similar or random parts (ie. unitisation), the amount of parts it contains, and the index of each part in the aggregate respectively to their order of instantiation. Unitisation U and amounts $A$are set once in a header: U_A, and indexes I are added to the representation of the token so that a latent representation for an aggregate would be following the notation in Equation (16).

$$U - AI_1, [S_0B, B_s, [B_x, B_y, B_z], [B_\phi, B_\beta, B_\alpha, B_\gamma], S_MB] ... I_A, [S_0B, B_s, [B_x, B_y, B_z], [B_\phi, B_\beta, B_\alpha, B_\gamma], S_MB] \tag{16}$$

With this approach, we appeal to more general unsupervised learning methods and where the generative modeling of sequences can be pursued. This is generally the case for models such as *Recurrent Neural Networks* (RNN) (Graves and Schmidhuber, 2008), *Long-Short Term Memory* (LSTM)(Hochreiter and Schmidhuber, 1997), *Gated Recurrent Neural Networks* (GRNN) (Chung *et al.*, 2014), and lately *Transformers* models such as *Bidirectional Encoder Representations from Transformers* (BERT) (Devlin *et al.*, 2019) and *Generative Pre-trained Transformer* (GPT)(Radford, Narasimhan, *et al.*, 2018) where an *attention* mechanism is replacing *recurrence* (Vaswani *et al.*, 2017) and have been developed for modeling relations at miscellaneous degrees of distance within sequences (Hermann *et al.*, 2015; Bahdanau, Cho, and Bengio, 2016). While the performances of such recent models is constantly being evaluated and adapted on other kinds of data than originally *Natural Language Procesing* ones (NLP) which might be encoded into sequences (M. Chen *et al.*, 2020; Huang, Vaswani, *et al.*, 2018) their capacity for extending the length of outputs and attention is increasing (Child *et al.*, 2019). We will make use of the current capacities of a GPT-2 model (Radford, Wu, *et al.*, 2019) for designing an encoded structure of our data and integrating such model within our generative workflow. Further research will be looking for increasing computing performances. Accordingly, the structured dataset is fed to a *medium* GPT-2 pretrained model (24 layers, 1024 hidden layers, 16 attention heads, 355M parameters) for fine-tuning to lesser complex latent space accounting for 76690395 internal tokens within the generator. Every structured data parameter has been normalised to a fixed length of encoding characters (eg. $S_0B$is made of 4 characters with preceding zeros for lesser-than-thousand values), and float values have been rounded to a thousandth of the CAD unit while preceded by a polarity symbol (+/-) to enforce the polarity encoding. Similarly to text-based transformer encodings, where a header and footer markers indicate the bounds of the data, bounds have also been enforced in each part. After fine-tuning, the model may generate similar aggregates in a realistic fashion for visual scenes (see Figure 69).

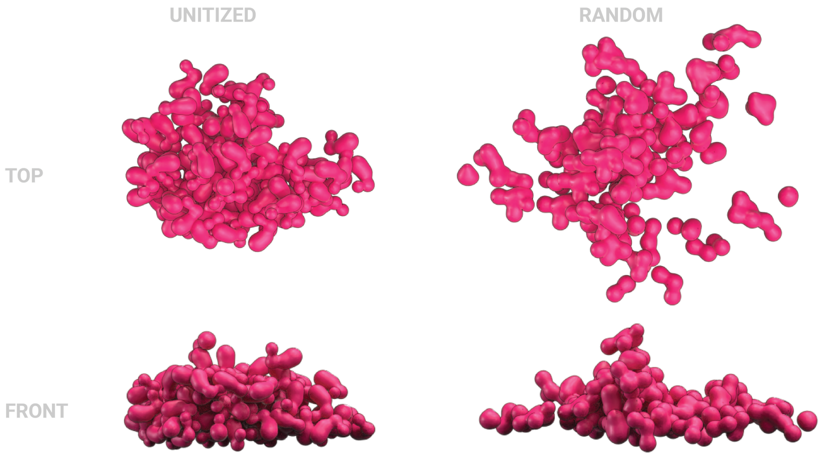


Figure 69: Samples of generated aggregates from the fine-tuned GPT-2M model. From Top to bottom and left to right: top and front view of a sample generated with unitised parts, top and front view of a sample generated with random parts.

Given the relatively small initial dataset, the pre-trained transformer appears to have learned the unsupervised DA, perceptually indifferentiable from the ground truth. We can further observe that the ground plane condition has also been learned alongside as a basic scene-to-part relationship (see Figure 70). And similarly, part-to-part and part-to-aggregate relationships appear to have been learned and can afford for the generation of new part tokens to present within our generative workflow (see Figure 71).

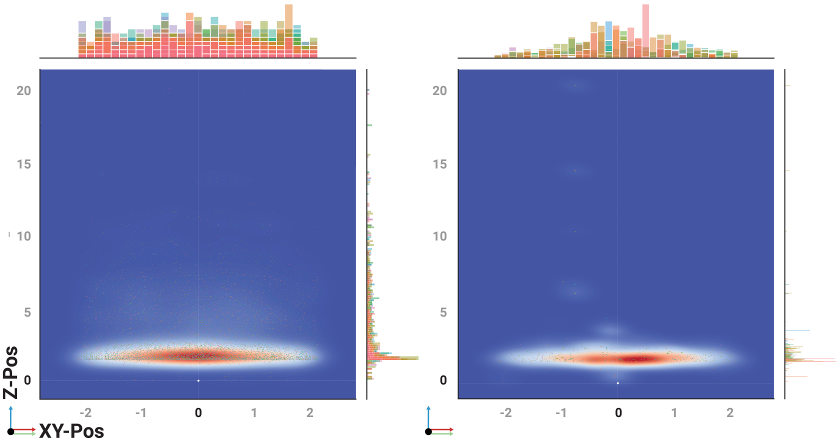


FIGURE 70: Representation of location variances for a single part. The XYZ location parameters are plotted on 2 axes where XY is being reduced to a vector of 1 dimension using T-SNE and plotted on the X axis, and Z is left unchanged and plotted on the Y axis. Each plot contains 10 000 parts picked randomly - Left: 10 000 first parts picked randomly from the initial dataset. - Right: 10 000 single parts generated from the trained model without any priors. The variance appears to shrink around the learned DA (z-axis origin, above XY plane origin).

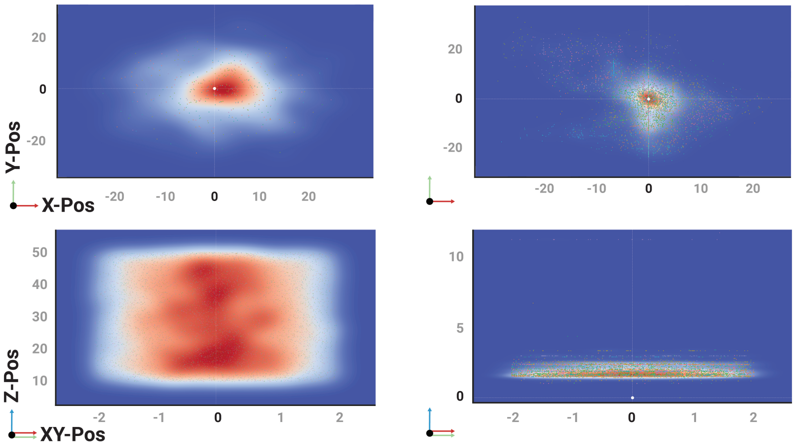


FIGURE 71: Representation of location variances for a single part generated from a prior part. - Top left: 10000 priors used as seed for generating new parts. - Top right: generated parts from priors with location plotted relative to their prior location. - Bottom Left: priors with randomised z location above ground. - Bottom right: generated parts from priors with absolute z location.

Once new part tokens have been generated, their latent representations are then being rendered by the same CAD engine which will retrieve their object representations and apply the generated spatial and graphic transformations to them. These will be presented in a RSVP-OP mode together with the prior aggregate (see section Presentation above) and further discriminated (see section Discrimination above). The discriminated part tokens will be sent back to the generator in order to concatenate their latent representation with the aggregate one in order to encode a new prior, and for the generator to progressively produce a growing sequence of aggregated token parts. Given the multiclass classification of the designed discriminator and the reduced amount of tokens to be presented compared to the overall latent space of generations, a decision function must be also set to allow for an exploration/exploitation strategy of generated and discriminated features (see Figure 72). And given the fact that received classified tokens are subordinate to human visual discrimination, as well as feedbacks about the cost of discrimination are only partial (ie. labels are hidden to the visual presentation) and cannot give a synoptic assessment to the user, we consider the decision function to be similiar of a *multi-arm bandit* (MAB) decision task (W. R. Thompson, 1933; Slivkins, 2019). This is generally the case for the computational study of human learning and reinforcement learning in the trade-off between gathering information and collecting rewards (Cohen, McClure, and Yu, 2007; Schulz and Gershman, 2019). Since this function is at the forefront of the generative process, its design should be pursuing two main goals: (1) supporting the improvement of classes separation in the discriminator by reacting to its output, and (2) improving the generation speed and relevance of generated aggregates by allocating new tokens to specific prior sequences and increasing the sequence range of tokens produced in one step. While the first goal involves also the way tokens would be presented as visual stimulus the later solely involves the generator. A wholly unified decision method would therefore have to include RSVP-OP parameters (see section Presentation above) and eventual fused feedbacks in its action definition in order to express a reward that is visually interpretable by a participant.Accordingly, MAB is also applied in similar sequence-based models for BCI such as visual spellers for improving overall performances (Kocanaogulları *et al.*, 2018). For simplicity and the first scheme of a model in this research, we will focus here on the second objective for the generative process and limit the decision method to an *active learning* (AL) technique where under partial observations and in the absence of explicit feedback, a label is provided by the participant.

Once a *seed* is being randomly generated at $T0$ from initial cued parameters, a first generation is done for a number of n part tokens $T1$ and presented for discrimination. The generator may produce a large amount of $T1$ but only a few may be presented at a given time to receive a class label C. The active learner must then apply a selection of T1 which should support the most confident labelling of the entire $T1$ distribution so that a maximum amount of priors can be sent back to the generator (see Figure 72). Since the generator is unsupervised by design and does not know to modulate its bias towards particular classes, the active learner decides on a new distribution of $T1$. By leveraging the multiclass discrimination, we can devise on a distribution prior tokens which were labelled as BAD $(Cb, eg.0.1$

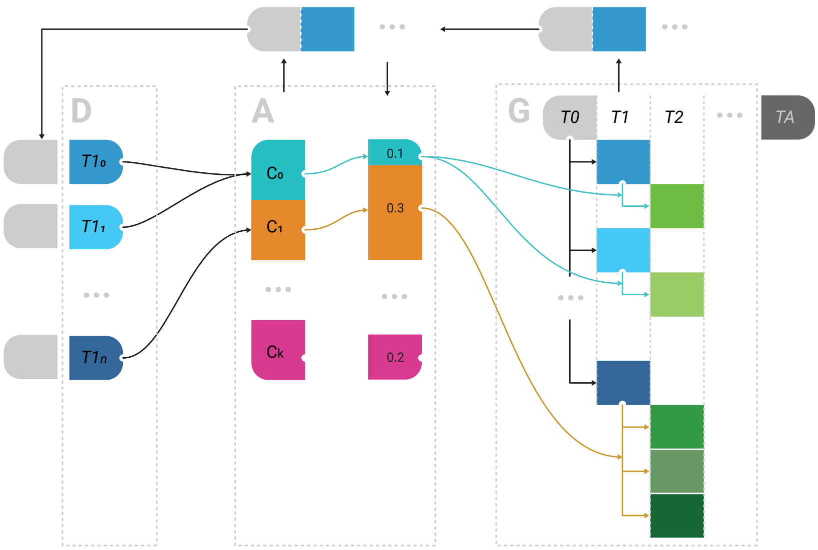


Figure 72: Flow diagram of the first iterative step. The generator G is producing n (eg. 30) part tokens T1 which are then being presented for discrimination together with the prior T0. The active learner A chooses the sample distribution of tokens to be presented based on uncertainty. A discriminator D is performing a multiclass classification, with k classes C, of the tokens in correlation to decoded ERP patterns. A receives the classified tokens and updates its weights with the given the new distribution. It then ponders the whole T1 distribution generated originally by G with a decision function to attribute the whole percentage (eg. C0: 0.1*n, C1:0.3*n) of new n part tokens T2 to G, generated from the combined priors of T0 and the corresponding T1. The loop continues until a specified limit TA in the sequence is reached. Accordingly, the decision function may modulate in time the distinct percentages to allow for an exploration/exploitation strategy of the generated tokens.

Results

As the previously described context of the AL relies on partial observations and non-stationarity of labels coming from the discriminator, the accuracy of classification for the AL over the entire generated batch may be subject to significant decreases in confidence probabilities for every new batch produced by the generator. However, since it is assumed that variance should be progressively reduced over the course of these iterations, every new label is being kept to increase the amount of known labeled data to teach the AL and produce a more confident classification (see Figure 73). In relation to that known prior distribution, the uncertainty sampling query strategy keeps selecting the most uncertain samples to adjust its decision boundaries.

Eventually, when a significant amount of iterations has been showing classification accuracy above a confidence index for some time, the generative loop may stop to prompt the discriminator for more input and feed directly the generator with new distributions based on its current accuracy. When it lowers again, the interactive loop involving visual discrimination may resume. This allows for increasing the speed of generative models and decreasing the mental efforts involved in such interaction, including increasing times of inter-sessions intervals due to the growing amount of tokens to be generated at every new iteration. By doing so, larger aggregates can be generated exploiting learned distributions. We understand this generative method also as a potent design method, where a certain period of necessary interaction builds momentum towards the task until a confidence threshold is reached and a

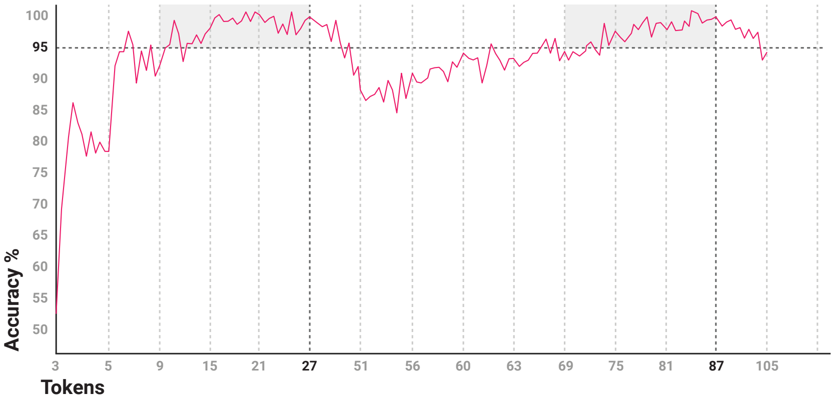


Figure 73: Accuracy plot of the evolution of the AL to classify generated samples over the course of the modeling sequence. While the accuracy starts quite low with very few labeled samples (ca. 0.51), it quickly increases in proportion to the amount of generated tokens. The amount of tokens added at every presentation step varies from 1 to 6 depending on the last measured accuracy. A confidence threshold is set (ie. 0.95) to evaluate whether or not the amount of generated tokens should decrease or increase. Once this threshold has been reached repeatedly for a certain amount of times (ie. 3 highlighted in grey), the generative loop stops asking the discriminator for labels and enters automatically in a closed loop between the generator and the AL (eg. From 27 tokens to 51, or from 87 to 105).

last presented token becomes a kind of fulcrum turning the generative loop in a closed one and pursuing on a predictive completion of the aggregate to the best of its confidence (see Figure 74).

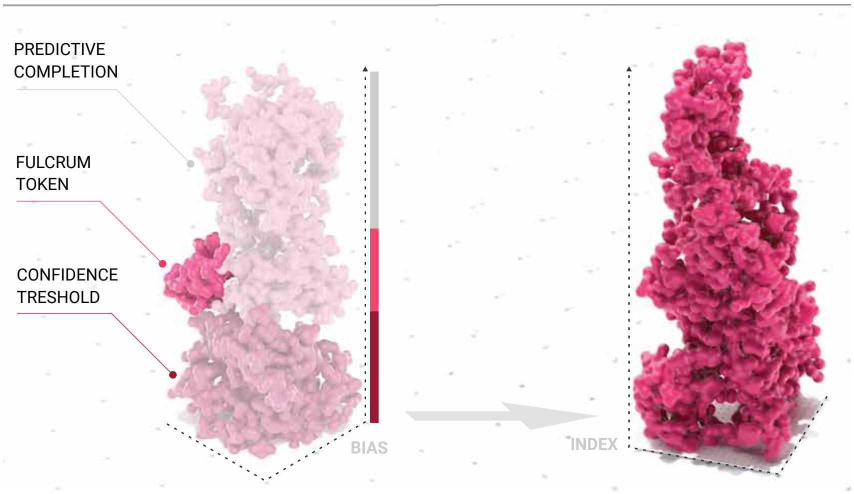


Figure 74: A schematic version of the generative sequence of design aggregates. Left - tokens are being presented iteratively until consecutive confidence thresholds are being reached. A last tokens presentation is being run with the maximum amount of tokens allowed to be generated at once and if the confidence is being maintained, the generative loop runs independently from the discriminator and human interaction and relies on predictive completion. Once the generation ends, the full aggregate may be considered in the distribution as an index of a particular design belief.

The moderated distribution of samples that is given back to the generator for a new iteration is modulating the generated distribution over time following the AL decisions. An interesting aspect of this method is not only to explore particular design beliefs but also to remove potentially bad samples which might violate DA along the generative cycle. For example some parts may be generated in bulk without any connection to prior aggregates and may be detected intuitively during the presentation (see Figure 75).

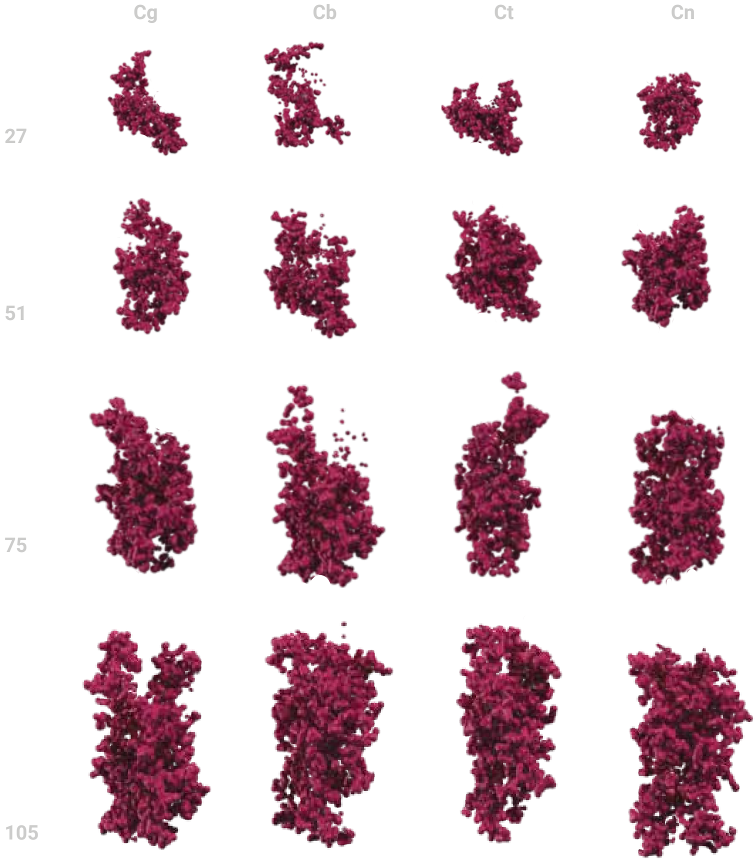


Figure 75: Samples of generated aggregates during the sequence. Each label is being used proportionally to modulate the generation of each potential new token labeled as Cg (GOOD), Cb (BAD), Ct (INTERESTING), Cn (NOT). Samples taken from generative steps at 27, 51, 75, 105 aggregated parts for each class. Aggregates may follow different paths depending on the generator parameters such as temperature.

Once a sample long enough has been produced, it may then be reused as a training sample for the generator to produce similar ones and fully exploit the learned beliefs to explore its design space. This technique can be deployed in two ways: to minimise the amount of interaction and mental efforts required by an attending participant to the task of visual discrimination in a demanding RSVP-OP context, and to further explore generated solutions to the extent of their variance (see Figure 76). By progressively biasing a generative model with inputs from neurophysiological data observed under covert responses, we might as well discover design solutions which would have not appeared under traditional modeling methods in CAAD.

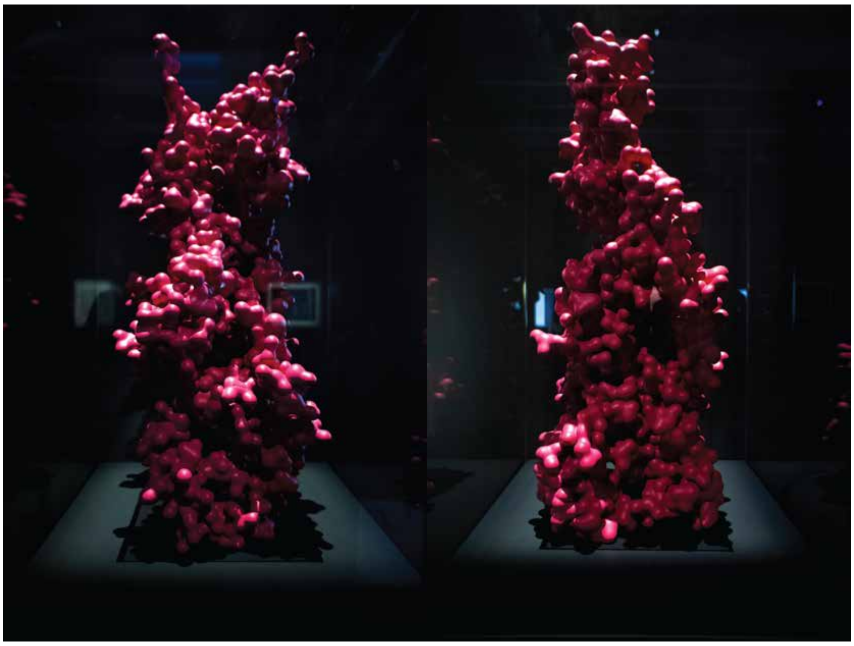


Figure 76: Photos of two physically produced aggregates from the experiment with a generative sequence extended to 400 parts. Left : an aggregate resulting from predictive completion following described methods. Right: an aggregate generated with the previous one as a training sample to index learned beliefs. All parts are individually post processed with connections comprised of magnet inclusions. Once coated, they are assembled together following the generative sequence and physically stand to gravity.

One important issue that the developed techniques have been trying to identify regards the accumulated degree of uncertainty that is constituted by three kinds of related distribution problems: 1 - a presentation distribution that must try to maintain a certain distribution across estimated classes to form stimulations which might trigger neural responses different enough to be later separated by a discriminator. 2 - a decision distribution which is consequently impacted by the limited amount of samples provided by the generator, and the degrees of non-stationarity and uncertainty present in the received labels. 3 - a progressively modulated distribution of the generator impacted by the selected samples from the AL. This causal chain occurring iteratively along the interactive loop constitutes a potential model for future investigations with reinforcement learning techniques. An interesting hypothesis to follow, given that some artefact may still be produced in relative significance to certain identifiable features of the given task is that, on the human end there is also a form of implicit adaptive learning occurring to reinforce responses eliciting appearing features. New designs for presentation paradigms and labeling should also incorporate mechanisms that help separating and stabilize these responses into a finite cardinality.

3.3 SUMMARY

Current technologies involved in the field of BCI relate to basic ideas of exploring sensed information, enhancing or rehabilitating such capacity. To that end, they support a common intent with architectural modeling in articulating significance through ICT. An extensive literature review of research about interfacing the human brain with computers has been presented a the beginning of this chapter in a complementary fashion to the CS literature explored in the previous chapters in efforts to bind these two fields. While BCI has positively progressed in its research, its widespread applicability remains slow due to many challenges deeply linked to the way we are modeling artificial aspects of learning and considering the usability of such interface in emulating our own intelligent capacities in everyday tasks. Architecture is no easy task at any point of its process and constitutes a great challenge for the integration of both. The aim of this chapter was to both identify plausible means to do so for the present research and future experiments, and explore some of them in the way they might support previously developed vocabulary in architectural modeling.

What the review for corollary references revealed is the vastness of techniques and their plausible combinations presently being researched and discussed. Generalisations, while being present, seem to cover only partial aspects of the mind processes and rely on both human and artificial understandings of intelligence to become operative, as the dimensionality of one never fully intersect with the other. In a rather unconventional way, the sought BCI techniques have been gathered into sections which do not necessarily follow a typical linear path from neural phenomena to their decoding, but rather reframed into topics that seemed better formulated for the present research in the ways of acquiring brain-related data, the dual conditions of learning and literacy, the known neural phenomena of interest, their related signal processing and methods of measurement.

From there, a general hybrid framework has been schemed in the perspective of supporting the present research as well as future work and collaborations in its pursuit. As a most architecturally relevant, and information-rich, sensory modality, the framework has been limited to the visual field in the hypothesis that not only visual information should suffice to establish an adequate and minimal communication channel but also that it should relate to other types of content in elicited phenomena (eg. intuitional physics or semantics).

From degrees of invasiveness, size, cost, resolution, safety and portability, EEG acquisition techniques appeared to be the most viable and used ones for research holding the promise of non-clinical applications, at the moment, in both synchronous and asynchronous modes of interaction. Despite its poor SNR and spatial resolution, its high temporal resolution greatly supports the study of temporal neural phenomena and can be complemented with fNIRS due to its resolution inverse to EEG, and other modalities such as PPM for covert attention in the implementation to attentional switches in regards to the task at hand. Accordingly, a dual interactive mode was further designed. A main operative synchronous and reactive interaction supporting the study of generative design methods, and a secondary one, asynchronous and passive to adapt its ergonomics.

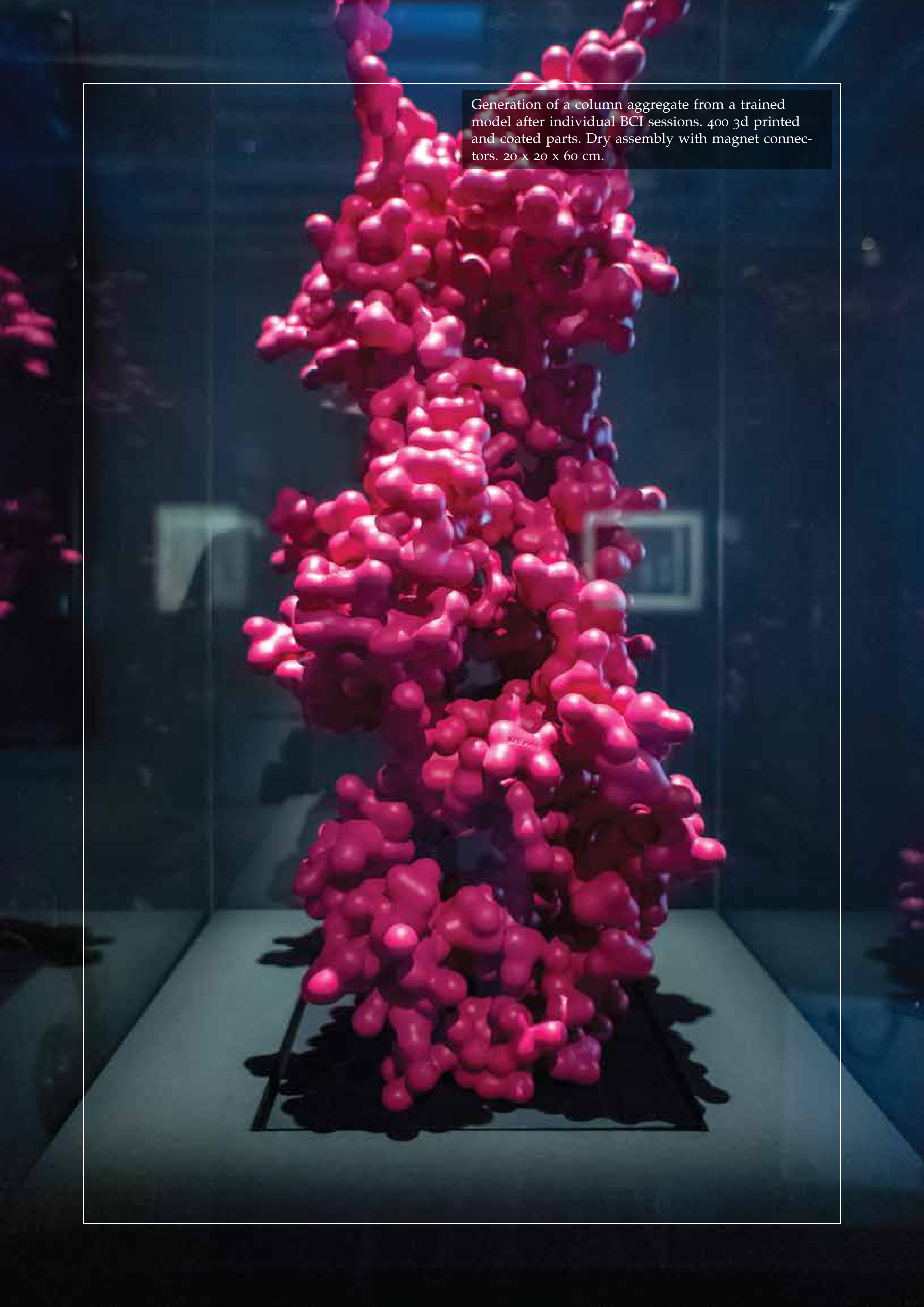
The dual condition of literacy and the way it could be modulated through both subject and machine adaptations in BCI tasks, can be broadly organised among different types of interaction, responses, stimuli and presentation. Interactivity is here mainly considered by levels of involvement from a subject's neural activity and its synchronisation with computer-based elicitations. Combinations were suggested as a way to support both the learning of a visual discrimination task under selective attention and synchronous reactive modes of interaction with RSVP, and adapting its ergonomics over time under operant conditioning and asynchronous passive interactions. For avoiding the increase of visual fatigue and help to maintain attention, motion-based implementations of RSVP have been suggested. In order to favour further attention and immersion, a complementary hypothesis was formulated in combining task presentation and feedback together for more sophisticated elicitations and future research perspectives. Additionally, when RSVP parameters thresholds allow for it, an additional SSVEP at the presentation frequency, if found, could be used to identify task attendance and control the flow of interaction. Under such level of visual complexity found in CAAD tasks, certain decision methods should also be studied in order to maintain a decent flow.

Incidentally, the synchronicity of a particular BCI is tied to the kind of neural responses that is expected. Whether exogenous while attending a stimulus external to the subject and under selective attention, or endogenous and self-paced, they relate to miscellaneous mentation types ranging from motor activity to object categorisation. Endogenous responses in non-clinical studies are good for assessing the continuous modulation of cognitive states and mental resources. Transient exogenous responses are particularly good for reactive interactions and discrete types of stimulus presentation. The richness of ERP components, the lack of amount of necessary training, and its detection across modalities, allow for numerous task designs. In the perspective of developing multiclass discrimination tasks for CAAD modeling, the whole spectrum of ERP components is considered. The hypothesis that under a certain frequency range of RSVP, steady state potentials might appear is maintained for future testing the design of a frictionless switch via the assesment of task attendance as well. Signal preprocessing is considered to its minimum and aimed for mostly subject-independent designs and robust classifiers. Due to challenging conditions, RGC classification pipelines have been favoured as initial methods. Once an adequate configuration is found, adaptive designs should be sought.

The way adaptive methods can be approached concerns two types of learning which are co-dependent. A subject learning from use and inferences of the interface, and a computer learning from the variability of signals. Assistive methods can also be combined either to participate actively in the execution of the task, or diminishing its difficulty. In a co-dependent perspective, they would essentially support long-term improvements in the separation of decoded features. Similarly, regarding the machine pendant of this dual mode of learning, adaptive classification is sought to solve issues related to subject calibration through two aspects of the auto-calibration of a classifier’s weights, or the adaptation of its data-space via transfer learning. Both being particularly useful in studying the generalisation, over time, of learned patterns across sensory modes, tasks and subjects.

As a starting point, conducted experiments focused on the synchronous reactive mode and the integration of prototypical stimulus presentation for CAAD. The ambition was to explore found techniques and derive adaptations from the task of visually spelling words to growing shapes and aggregating parts in order to see how the previously developed vocabulary in a prototypical theory of architectural modeling with neural potentials would take form. It followed that, in order to reach an adequate and deeper understanding of this research implications, experiments should be supported by both software and hardware developments. The accessibility and portability of data acquisition, the signal preprocessing methods, data analysis and decoding pipelines, machine learning generative models, presentation paradigms have been implemented in a prototypical software offering an overview of the possibilities to study and combine every technical elements of the research into a practical interface which could not only serve the purpose of the presented experiments but also evolve further afterwards by providing a general framework to include future techniques. Similarly, hardware has been sought to be practical and evolutive by exploring DYI and off-the-shelf solutions with additional design and programming developments to augment their capacities during experiments. Their goal was purely didactic and will not be pursued further to give more room to visual modeling techniques software development and integration to the CAAD ecosystem.

Regarding visual modeling with BCI, the initial reason that the P300 speller was chosen as the first experiment was regarding its rather stable literature and accessibility, as well as a first approach on how to articulate visual characters without explicit grammars. This was our first entry into interpreting visual information as the primary vessel for producing architectonic relations in that fashion. From there, BCI started to be explored in its details and the way computational communication models are being applied and generalised. The particular way in which visual tokens discrimination techniques were devised with RSVP-OP offered an opportunity to start adapting its structure and paradigm for more visually complex tasks going towards the domain of durational aesthetics. From this presentation paradigm, iterative and generative modeling methods could be approached and where each generated design state may be presented as a token to be discriminated visually for aesthetic significance in a rather unconstrained and explorative fashion based purely on visual memory capacities and related neural potentials. The second experiment designed to explore the modeling of growing shapes allowed to approach a way to find the emergence of belief formations related to subjective significance and separated from generative randomness. This idea appears to be promising and should be developed further in assessing a user's subjective preferences towards peculiar designs in the vastness of a generated solution space, together with adaptive methods to support their timely evolution. Eventually, RSVP-OP should be further developed in a way that supports such adaptation, and the generalisation of visual architectural modeling tasks. While a few simple examples have been described in the experiments, the vastness of their range still constitutes a great challenge. On the more particular task of aggregating parts, the last experiment has shown that it is possible to learn implicit features from architectural concepts and which come entirely from an individual's mind. In addition to design rules of aggregation related to parts and scenes, or design affordances that can be either pre-specified or inferred on generatively, these categorical features can be implemented in a way that modulates the weights of a generative model and progressively adjust produced designs towards subjective preferences and specifies the solution domains around significant categorical features. Should these preferences evolve also over time and across individuals is an expressed interest in the continuation of this research to allow such machine to emulate architectural modeling explorations.



Generation of a column aggregate from a trained model after individual BCI sessions. 400 3d printed and coated parts. Dry assembly with magnet connectors. 20 x 20 x 60 cm.

CONCLUSIONS 4

4.1 A SYNTHESIZED CONTRIBUTION

What has been extensively developed in the previous chapters now calls for a synthetic reformulation. As each chapter was already extended with a reflexive summary, the main task of this conclusive section will be to abstract the main arguments and contribution into perspective. We have been gathering ideas across CS and humanities about the modeling of intelligence and which have formed our contemporary conditions in the face of ICT, and revealed how intimately related they are to the way computation and compositionality are approached in architecture. The hypothesis that was carried out throughout the thesis was about the untapped potentials of the human mind in composing under uncertainty. Retroactively, a good question to ask the reader in order to appreciate the intented contribution fo rthis thesis is to ask how one could model (architecturally) anything at all without the grasp of pre-specificty? Why would we need such thing and if so what would allow such capacity? The initial aim of the thesis was to unfold a duplicit picture held by the term *potential* and regarding the way it characterizes both a modality of information and its capacity for communication across natural and artificial modes. It emerged from the richness of the debates held around the modeling of intelligence and the intractable power of the mind in creating values from a *thing-in-the-world*, to an *object-in-the-mind* and back to an *object-in-the-world*. Computational theories can be seen as perpetually incomplete and constantly in search of a coherent equivalence. Paradoxically, this is that incompleteness which has fuelled their progress and also characterizes a necessary complementarity with the object of study: *thought*. That particular object holds non-computability as a core feature. The reconciliation of both *intelligent humans* and *artificial intelligence* in ICT is the promise of progress in our own understanding of intelligence and what it still has to offer. What we have found and emphasized is that not only it is of architectural relevance, but it supports a technology which might become beneficial for architectural modeling and perhaps for every practical task which has to deal with compositionality in the physical world. And more fundamentally, architectural modeling itself is prototypical because its basic architectonic operations are already present at the edge of memory, where fleeting representations exist. Architecture is better thought as a communication process and, followingly, better concerned with the flows of significance, its polysemy and intractabililty. Beyond traditionally shallow analogical means of articulating meaning spatially in architecture, computational/representational frameworks offer more potent ways to deal with it while coding with symbolic/algorithmic representations and operating in the temporal dynamics of the mind. The ones that allow for the discursivity of representations to flow prior to syntactic structurations. In general, pre-specifc structures do not have the capacity to characterize a thought process. It is better thought as simply as an emergent and probabilistic structure rather than a primarily constructive one. The positions taken and arguments developed along these vectors are also the ones that shaped and were informed by conducted experiments. An impatient reader in search of physical outcomes might tend to think that the present research is specifically oriented towards the applications of BCI in Architecture. The research field of BCI is overall sympathetic to our own motivations in integrating human capacities in operational computational frameworks. However, second thoughts might come quickly when recalling the path we have taken in describing the way the idea of modeling has been considered so far as intimately linked with the one of pre-specificity. Even when not explicitly formulated, this is too often that the lack of care in considering the necessarily high level of abstraction in which pre-specificity must operate, has severed progress in extending the power of architectonics in our own thoughts and practices. What a transdisciplinary research allowed here, was to confront moments of architectural thinking with their scientific correlates, and to open the reflection to a much wider extent and significance. And bring back architecture in tune with agencies of time and frequency domains of truly operative architectonics. The role of investigating the research in BCI was to propose a practical counterpart to the prototypical theory we have been developing and in the hope that it would support the emulation of greater capacities in architectural modeling. The found BCI model based on visual and exogenous principles serve that purpose and lay grounds for future technical developments (see Figure 77). What we have found there, supports theoretic arguments and bring a hopeful but challenging future in the research of its sophistication and practicality. As a first step in that direction, we have designed and argued for a coherent interaction model that characterizes architectonics features in both its syncretic and synthetic aspects and by combining the power of human visual discrimination and the generativity of artificial intelligence in a co-dependent closed-loop dealing probabilistically with uncertainty. The analogy of inverse graphics has provided for a mean to generate compositionality from code and bridges the conjugation of IH and AI framed by a GRAD model as a generalisation of creative, interactive and generative processes appraising these modes. By design, the model represents an instrument of navigation among the vastness of generative design spaces and which, can now be called a compass. For its general axis remains oriented along the dynamics of an individual human and, within the flows of his relations to the world, is pointing towards an open horizon of dynmaic magnitudes. As any other instrument, specific vocabulary must be employed to define its experience. And since architectural modeling is best understood as a minimal linguistic code, its transformative power resides in the very same vocabulary. Within that scope, we have gathered our focus on translating the idea of *part* towards the one of a *token* and the one of an *assembled* object towards the one of a timely *aggregate*. The gained *significance* of time by these aggregates shall be modulated by the weight of *beliefs* and relate to particular concepts of modeling. In that sense, it encompasses a reapparaised perspective of *durational* aesthetics in the 21st century, brings about *organicity* in modeling and emulates *compositionality* under attention. Now comes the time to consider that the expression *a gestalt in the making* might have found its most potent agency.

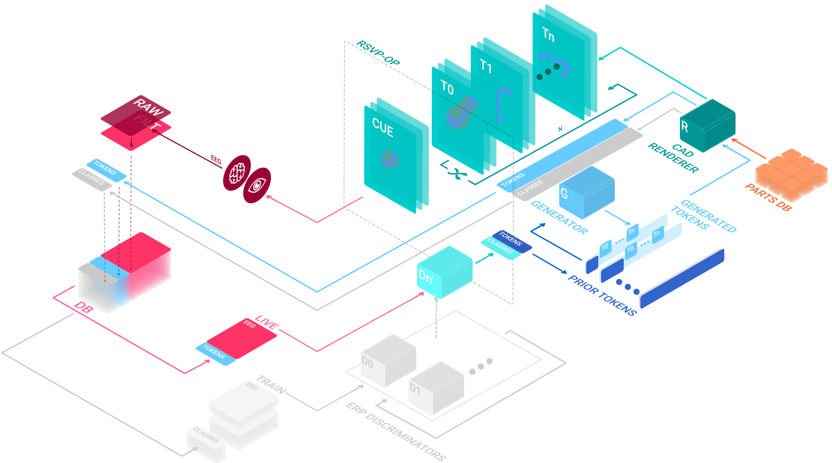


Figure 77: General diagram of the informational flow involved in the developed BCI model. Based on visual and exogenous modes, the diagram combines every technical components of the thesis and its experiments. It follows the GRAD model in a more detailed way from data acquisition (left) to feature discrimination (bottom), tokens generation (right) and visual presentation (top).

Throughout the discrete synthesis of the summaries, we have previously mentioned several technical aspects worth of further investigation. They have been nonetheless part of this research in efforts to identify and pre-establish aspects of improvement in testing the developed arguments. Eventually, the vision we hold is for implementing such technology in architectural modeling practice in order to enrich design phases or intermittent interactions with machines across phases for qualitative inputs on design tasks ranging from early design to onsite fabrication. It is also seen as a way to communicate more fluently with computers and their generative capacities. The challenges involved in implementing increasingly sophisticated visual tasks greatly influence the capacity of the overall interaction in exchanging information fluently between humans and computers. Eventually, future paradigms should be designed and generalized in a way that the cardinality of decoded discriminative patterns should be stabilised to a handful range of logical outputs. Following our research, and in reference to the ones of FINST and LOT, we suggest that this cardinality should be ranging from a handful of 2 to 4 in expressing formed beliefs towards solutions of significance, and allow for the design of adaptive decoding methods from binary to quadratic classification at most and express the evolving formation of design beliefs regarding their relevance to that task and peculiar tokens expressing novelty and exploration orientations. To that end, further research should be conducted in identifying such methods for stabilisation in their capacity for generalisation. We provisionally divide this assumption in two hypothesis that we name here the *hand of beliefs hypothesis* (regarding the finite cardinality of finite patterns), and the *hypothesis of greater variance* (regarding the production of design solutions of greater variance in their outcomes by using such interaction model). Eventually studies would gain in significance themselves by establishing longitudinal experiments to observe the evolution of such techniques over time and their emulating capacities. Overall it is yet early to assume that such technology might be beneficial in producing more fluency and variance than other traditional approaches but there should not be any better reason to conduct and pursue such research than to find this out. Greater variance is after all, a hypothesis assumed for the most basic benefits of any research in interactions that has overcome the primitive idea of control to embrace communication as a greater capacity.

LIST OF FIGURES

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BIBLIOGRAPHY 5

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