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PhD Dissertation

FREEHAND DIGITAL DRAWING: A BOOST TO CREATIVE DESIGN

THE OBSERVER'S EYE AND THE DRAFTSMAN'S BRAIN

Gaia Leandri

Directors:

Francisco Juan Vidal (Universitat Politècnica de València)
Susana Iñarra Abad (Universitat Politècnica de València)
Angelo Schenone (Università degli Studi di Genova)

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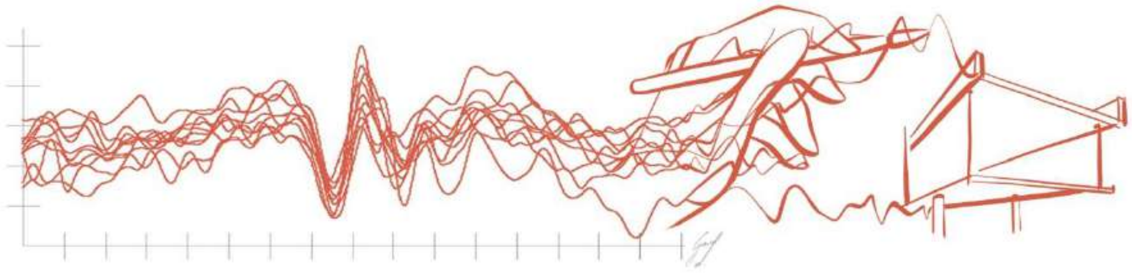

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Doctorate in Arquitectura, Edificación, Urbanismo y Paisaje
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Oftalmologia, Genetica e Scienze Materno Infantili
Università degli Studi di Genova

Directors:

Prof. Francisco Juan Vidal (Universitat Politècnica de València)
Prof. Susana Iñarra Abad (Universitat Politècnica de València)
Prof. Angelo Schenone (Università degli Studi di Genova)

Tutoring

Prof. Francisco Juan Vidal (Universitat Politècnica de València)
Prof. Susana Iñarra Abad (Universitat Politècnica de València)
Prof. Angelo Schenone ((Università degli Studi di Genova)
Prof. Enrica Bistagnino (Università degli Studi di Genova)

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Summary

The representation of an architectural project aims at several intents, one of the most relevant being the visualisation of a design. The subject of this dissertation is therefore the relationship between the draftsman, the creativity of his brain, the represented design, and the mind of the observer. Since the Eighties, architects, designers and scholars wondered whether the current habit of an ever increasing digitalisation could be detrimental or advantageous to such relationship. After an analysis of architectural imaging since the Renaissance, as reported in Part 1, the current techniques are reviewed and discussed. The first question, addressed in Part 2, has been whether the simulation of reality with renders of photographic quality, would relate to the observer better or worse than a traditionally hand drawn image. A questionnaire has been constructed to probe the communication and representation qualities of the images. The results suggested that these two qualities were best represented in the case of freehand drawing compared to photorealistic renders. Part 3 was focused on the designer and used the instruments provided by neuroscience, i.e. the EEG and 'evoked responses', to quantify the brain activity in connection with freehand and CAD drawing. Because the involved technology had never been applied before to a drawing subject, the investigation had to be divided into three separate experiments. The first one was dedicated to finding a reliable way to perform the recordings in subjects who freely moved their arm and hand while drawing. The second and third experiments were aimed at analysing the cerebral activity occurring before and after each drawing movement. All results demonstrated that a larger cerebral activity preceded and followed each movement in freehand drawing compared to CAD design. This finding may be considered a robust step towards the notion that also creativity may consequently be improved. The final conclusion is that the freehand drawn images make a better link between author and observer, and at the same time the very movement and haptic perception of the hand elicit creativity. Indeed, the most recent advances in technology of drawing tablets have provided a new medium for freehand drawing, which can exploit the capacity of data handling of computers with the natural movement of using pencil and paper, ending up in a traditional hand made product. A wise usage of modern technology can therefore merge the human factor with the digital world.

Resumen

La representación de un proyecto arquitectónico tiene diferentes finalidades, una de las más relevantes es su visualización. El tema de esta tesis es la relación entre el diseñador, su actividad cerebral durante la fase creativa, el proyecto representado y la mente del observador. La pregunta, planteada por arquitectos, diseñadores y académicos en los años ochenta y aún abierta a soluciones estimulantes, es una pregunta bien conocida sobre si la creciente digitalización puede ser perjudicial o beneficiosa para esta relación. Después de un análisis de la imagen en la arquitectura a partir del Renacimiento, informado en la Parte 1, se revisan y discuten las técnicas actuales de representación. La primera pregunta, abordada en la Parte 2, fue si la simulación de la realidad con renderizado de calidad fotográfica garantiza una visualización mejor o peor que una imagen tradicionalmente dibujada a mano. Se elaboró un cuestionario para verificar las características de comunicación y representación de las imágenes producidas con las dos técnicas. Los resultados mostraron que estas dos cualidades estaban más presentes en el caso del dibujo a mano alzada que en los renders fotorrealistas. La Parte 3 se centró en el diseñador y utilizó las herramientas proporcionadas por la neurociencia, a saber, el EEG y las 'respuestas evocadas', para cuantificar la actividad cerebral de alguien que hace un dibujo a mano alzada con respecto a CAD. Dado que la tecnología utilizada nunca antes se había aplicado a un sujeto al realizar un diseño, la investigación se dividió en tres experimentos separados. El primero se dedicó a encontrar una forma confiable de realizar registros durante el movimiento del miembro superior en la ejecución del dibujo; los experimentos segundo y tercero tenían como objetivo el análisis específico de la actividad cerebral que precede y sigue a los movimientos individuales de los signos trazados. Los resultados mostraron que la actividad motora relacionada con el dibujo a mano alzada estuvo acompañada por un aumento en la amplitud de las respuestas electroencefalográficas en comparación con el dibujo con CAD. Este dato es probablemente un importante paso adelante a favor de la hipótesis de que la creatividad también puede mejorarse mediante el movimiento en el dibujo a mano alzada. La conclusión es que las imágenes así dibujadas crean una mejor correspondencia entre el autor y el observador, y que el movimiento y la percepción sensorial de la mano pueden fomentar la creatividad. Recientemente, los avances en la técnica de las tabletas de dibujo han proporcionado una nueva técnica para el dibujo a mano alzada, donde se combina la capacidad de gestión de datos del ordenador con los gestos naturales tradicionalmente ligados al uso del papel y el lápiz. de la tecnología moderna puede fusionar el factor humano junto con las nuevas tecnologías digitales.

Resum

La representació d'un projecte arquitectònic té diferents finalitats, una de les més rellevants és la seva visualització. El tema d'aquesta tesi és la relació entre el dissenyador, la seva activitat cerebral durant la fase creativa, el projecte representat i la ment de l'observador. La pregunta, plantejada per arquitectes, dissenyadors i estudiosos als anys vuitanta i encara oberta a solucions estimulants, és una qüestió ben coneguda si augmentar la digitalització pot ser perjudicial o beneficiós per a aquesta relació. Després d'una anàlisi de la imatge en arquitectura a partir del període renaixentista, informada a la part 1, es revisen i discuteixen les tècniques de representació actuals. La primera pregunta, abordada a la part 2, va ser si la simulació de la realitat amb renderització de qualitat fotogràfica garanteix una visualització millor o pitjor que una imatge tradicionalment dibuixada a mà. Es va elaborar un qüestionari per comprovar les característiques de comunicació i representació de les imatges produïdes amb les dues tècniques. Els resultats van mostrar que aquestes dues qualitats estaven més presents en el cas del dibuix a mà alçada que en els renders fotorealistes. La part 3 es va centrar en el dissenyador i va utilitzar les eines proporcionades per la neurociència, és a dir, l'EEG i les 'respostes evocades', per quantificar l'activitat cerebral d'algú que realitza un dibuix a mà alçada respecte al CAD. Com que la tecnologia utilitzada mai abans s'havia aplicat a un tema mentre es feia un disseny, la investigació es va dividir en tres experiments separats. El primer es va dedicar a trobar una manera fiable de fer enregistraments durant el moviment de l'extremitat superior en l'execució del dibuix; el segon i el tercer experiment estaven dirigits a l'anàlisi específica de l'activitat cerebral que precedeix i segueix els moviments individuals dels signes traçats. Els resultats van mostrar que l'activitat motora relacionada amb el dibuix a mà alçada va anar acompanyada d'un augment de l'amplitud de les respostes electroencefalogràfiques en comparació amb el dibuix amb CAD. Aquesta dada és probablement un pas endavant significatiu a favor de la hipòtesi que la creativitat també es pot millorar amb el moviment en el dibuix a mà alçada. La conclusió és que les imatges dibuixades d'aquesta manera creen una millor correspondència entre autor i observador, i que el moviment i la percepció sensorial de la mà poden fomentar la creativitat. Recentment, els avenços en la tècnica de dibuix a tauletes han aportat una nova tècnica de dibuix a mà alçada, on la capacitat de gestió de dades de l'ordinador es combina amb els gestos naturals tradicionalment vinculats a l'ús del paper i el llapis. de la tecnologia moderna pot fusionar el factor humà amb les noves tecnologies digitals.

Riassunto

La rappresentazione di un progetto architettonico ha diversi intenti, uno dei più rilevanti è la sua visualizzazione. Oggetto di questa dissertazione è il rapporto tra il disegnatore, la sua attività cerebrale durante la fase creativa, il progetto rappresentato e la mente dell'osservatore. E' ben nota la questione, sorta da parte di architetti, designers e studiosi negli anni Ottanta e tuttora aperta a stimolanti soluzioni, se una crescente digitalizzazione possa essere dannosa o vantaggiosa per tale relazione. Dopo un'analisi dell'immagine in architettura a partire dall'epoca rinascimentale, riportata nella Parte 1, vengono riviste e discusse le attuali tecniche di rappresentazione. La prima questione, affrontata nella Parte 2, è stata se la simulazione della realtà con rendering di qualità fotografica garantisca una visualizzazione migliore o peggiore, rispetto a un'immagine tradizionalmente disegnata a mano. È stato predisposto un questionario per verificare le caratteristiche comunicative e di rappresentazione delle immagini prodotte con le due tecniche. I risultati hanno mostrato che queste due qualità erano maggiormente presenti nel caso del disegno a mano libera rispetto ai render fotorealistici. La Parte 3 è stata incentrata sul designer e ha utilizzato gli strumenti forniti dalle neuroscienze, ovvero l'EEG e le 'risposte evocate', allo scopo di quantificare l'attività cerebrale di colui che realizza un disegno a mano libera rispetto al CAD. Poiché la tecnologia utilizzata non era mai stata applicata in precedenza a un soggetto mentre effettuava un disegno, l'indagine è stata suddivisa in tre esperimenti separati. Il primo è stato dedicato a trovare un modo affidabile per eseguire le registrazioni durante il movimento dell'arto superiore nella esecuzione del disegno; il secondo e il terzo esperimento sono stati finalizzati all'analisi specifica dell'attività cerebrale precedente e successiva ai singoli movimenti dei segni tracciati. I risultati hanno dimostrato che l'attività motoria collegata con il disegno a mano libera era accompagnata da un incremento dell'ampiezza delle risposte elettroencefalografiche rispetto al disegno con il CAD. Questo dato è probabilmente un passo avanti significativo a favore dell'ipotesi che anche la creatività possa essere migliorata dal movimento nel disegno a mano libera. La conclusione è che le immagini disegnate con questa modalità creano una migliore rispondenza tra autore e osservatore, e che movimento e percezione sensoriale della mano possono favorire la creatività. Recentemente, i progressi nella tecnica delle *drawing tablets* hanno fornito una nuova tecnica per il disegno a mano libera, ove la capacità di gestione dati del computer si abbina ai gesti naturali tradizionalmente legati all'uso di carta e matita.. In questo modo, un uso sapiente della tecnologia moderna può fondere insieme il fattore umano con le nuove tecnologie digitali.

Published Content

Part of the intellectual and experimental content of this thesis has been the object of publication in journals and presentations at meetings.

Peer reviewed publications:

Leandri, G., Schenone, A. and Leandri, M. (2021) 'Detection of movement related cortical potentials in freehand drawing on digital tablet', *Journal of Neuroscience Methods*, 360, p. 109231. doi:10.1016/j.jneumeth.2021.109231.

Leandri, G. (2021) 'Architecture and digital drawing tablets, bringing back human control over HAL', in Domenech, J., Merello, P., and De la Poza, E. (eds) *7th International Conference on Higher Education Advances (HEAd'21)*. València: Universitat Politècnica de València, pp. 957–965. Available at:

http://ocs.editorial.upv.es/index.php/HEAD/HEAd21/paper/view/12700

Leandri, G. *et al.* (in press, accepted on 3rd April 2022) 'Architectural representation: the image and the sign', in Domenech, J. (ed.) *8th International Conference on Higher Education Advances (HEAd'22)*. València: Universitat Politècnica de València.

Leandri, G. *et al.* (in press, accepted on 17th May 2022) 'The architect's brain and the thinking hand', *EGA-Revista de Expresión Grafica Arquitectonica*

Peer reviewed presentations at meetings with abstract or full paper:

Leandri, G. *et al.* (2021) 'Movement related cortical potentials and meaningful drawing', *Journal of the Neurological Sciences*, 429, p. 118. doi:10.1016/j.jns.2021.118555. Presented at the , XXV World Congress of Neurology. Rome, 3-7 October 2021

Leandri, G., Stara, S. and Leandri, M. (2022) 'EEG Patterns Related to Drawing Saliency in Design'. *ICNA 2022: XVI. International Conference on Neuroscience for Architecture*, Athens, 7-8 April.

Leandri, G. 'Representation of urban spaces: handcrafts and postcards'. Conference on *Algoritmi dello sguardo. Il paesaggio urbano tra rappresentazione e Progetto*. Dipartimento Architettura e Design, University of Genova and Ecole Nationale Supérieure d'Architecture Versailles. 29-30 aprile 2022. Full lenght paper in Proceedings

Leandri, G. 'The hand as a cognitive visualiser instrument *'Meeting of CiVIS, Centre for Visuality, La Visualità all'intersezione delle discipline umanistiche e tecnologiche*. Genova, 16 February 2022.

Introduction

Part 1 Drawing and Design

Part 2 Questionnaire on architectural imagery

General Conclusions and Future Research

Conclusiones generales y futuras investigaciones

Conclusioni generali e ricerche future

INTRODUCTION

Foreword

Objectives

Structure of the thesis

Foreword

This thesis reports the results of the research performed in accomplishment of the investigation programme pertaining to the double international doctorate as per agreement between the Universitat Politècnica de València, Spain (Departamento de Expresión Gráfica Arquitectónica) and the Università degli Studi di Genova, Italy (Dipartimento di Neuroscienze, Riabilitazione, Oftalmologia, Genetica e Scienze Materno Infantili) in cotutorage with the Dipartimento di Architettura e Design dell'Università degli Studi di Genova. The two doctorate courses are the Doctorate in Arquitectura, Edificación, Urbanística y Paisaje (UPV) and the Doctorate in Neuroscience (UNIGE). Blending the sciences of architecture and design with neuroscience is a new approach stemmed from the growing need of seeking the biological basis of the creative act on one side and the user's reaction on the other. Understanding the relationships between the designer, the craft and the customer will help to develop new design styles and architectural expressions agreeable to the human mind and physical requirements. At the same time, tackling the creative process with its underlying mechanisms will set a path for professionals and academics in an age when digitalisation is replacing most of the traditional techniques. The extremely fast development of new instruments opens new chances of expression, but at the same time restricts the choices within a preset frame of software and hardware. There are features in technology that may limit rather than boost creativity. Such drawbacks may be overcome, provided the brain operational steps are known and conditions set for the best performance. Fortunately, recent progress in neuroscience allows now innocuous exploration of brain functions in most natural conditions, and new knowledge is now available about links between cortical areas, cognition, and environmental influence. The new electrophysiological instruments now available have been used in this thesis, after some modification, to explore what are thought to be the first steps of the creative process, seeking differences according to the methodology in designing. The thesis is focused on creativity related to drawing, the main activity of the designer's expression. Before reporting the results of the investigation performed, however, a summary of uses and trends in architectural imagery will be given in Part 1.

The illustration is traditionally considered a part of the design process. From rough sketches to working drawings and renders, the designer gradually develops his ideas to enact them into the final object. But the very meaning of the visual product underwent transformations over the centuries according to the development of technical devices, changes in social background, and the impact of artistic movements. This graphic expression features elements from various cultural fields: besides art and illustrative techniques, it encompasses architectural history, psychology, brain physiology, theory of communication and marketing. Since the 80s of the last century, the attention of architects, designers and scholars concentrated on the meaning and inner features of representations, seen as a visual expressive tool of the drawer's ideas, with strong cognitive implications on account of the observer. The world of architectural images was no more considered an unbiased source of information. Ethical, social, and cultural values ought to be taken into account when designing and representing buildings and crafts. In the period of transition from analog to digital representation, these issues were the subject of a large amount of literature tackling a new approach to architectural visualisation. The opinions of scholars and professionals about the new possibilities offered by computers in comparison to the old manual systems do not always agree (Bernath, 2007; Ivarsson, 2010; Jacob, 2017; Lawson, 2002; Pallasmaa, 2009; Scheer, 2014). Recently, the almost abandoned freehand drawing has found new appreciation as a creative tool to convey the personal touch of the designer, whether it portrays a real or visionary project. Whatever the nature of the image chosen to reproduce architecture, be it hand drawn or computer made, the general attention has usually focused on the effect that it would yield on the observer. The quality of onlooker's perception has been investigated in a number of works aimed at a scientific assessment (Alexiou et al., 2009; Axelsson, 2007; Barry, 2006; Bates-Brkljac, 2009; Iñarra Abad, 2014; Llinares Millan and Iñarra Abad, 2014). However, if the image is the chosen means of communication between the author and the public, then the viewpoint of the author should also be considered. It is to be expected that the technique chosen to craft the image will deeply affect the making of the drawing itself and its ability not only to communicate but also to nurture novel ideas in the author's mind, in a sort of positive feedback effect. Such notions are the basis of the experiments reported in this thesis.

Objectives

The main objective of the thesis is to provide evidence about the differences between freehand drawn and computer generated images relative both to the designers and the observers, the two protagonists of the project creative process. Two types of experiments have been devised to accomplish as many secondary objectives. The first secondary objective was related to the question of how well a freehand drawn image would communicate and represent the designer's ideas and style compared to a photographic quality render. The second secondary objective was to provide neurophysiological experimental evidence supporting the hypothesis that hand movements could enhance the cognitive processes of the designer's brain. Other detailed objectives had to be tackled in the setting up of the tests and experiments and are described in Part 2 and Part 3. All methodology is also reported in the same sections.

Structure of the thesis

This thesis is divided into three parts; after a preliminary excursus (Part 1) on the features of architectural representations tackling the dichotomy between hand drawn images and modern photographic quality renders, there come two parts reporting the results of a simple Web test (Part 2) and neurophysiological experiments (Part 3). The general objective has been that of providing experimental evidence regarding the cognitive process of both the crafter and the observer of architectural images. To do so, an unusual test method and a new neurophysiological technique have been devised.

Part 1 explores the purpose of architectural drawing as a means of visual communication and presents an overview of selected illustrations focusing on the process of image-making. Nowadays the pervasive presence of mass media and the general use of increasingly sophisticated digital graphics has changed the way designers used to work, switching from hand made drawings into computer aided design and finally into digital simulations. In the last two decades, sophisticated photorealistic renders have arisen the enthusiasm of architects and the lay public for their seducing appearance. Nevertheless, there are now concerns about their actual ability to communicate the designer's ideas and style, and there have been warnings about the risk that the project's final image may get out of the designer's control, becoming the reference point of the project itself and changing the sequential relationship of the design stages.

Part 2 reports the results of a simple test meant to answer whether communication of the architect's idea of a building and representation of the architect's personal style are best conveyed by a hand drawn image or a photorealistic render. The test has been designed so that the answers were related to the responder's ability to match images and not to subjective opinions. In this way the test differed from most published material oriented on descriptive qualities of the images. The test showed that freehand drawing communicated more significantly than photorealistic renders the architect's ideas and style.

Part 3 concerns the neurophysiological study which, in turn, is divided into three experiments. The first one is devoted to testing a new method to record electroencephalographic signals during freehand drawing. The second one is related to the exploration of electroencephalographic changes between freehand and CAD drawing before each movement. The third investigates the electroencephalogram after each drawing movement, still comparing freehand and CAD techniques. The detected changes both before and after each drawing movement suggest that in freehand drawing there is a higher level of cognitive activity on the motor side, possibly being led by the hand sensory afferent signals. This evidence supports the notion that movements and haptic perception in the freehand drawing are relevant to cognitive processes possibly leading to creativity in design.

General conclusions

Discussion and conclusions of tests and experiments are written separately for Part 2 and Part 3. A general conclusion is also reported in a separate section tackling the issue of the achievement of the main objective and the future research that still will be needed and that may stem from the obtained results.

References

Full references of all the citations in Part 1, 2 and 3 are reported here.

Annexes

Source data of the survey test and of neurophysiological experiments are reported in Annexes 1 and 2.

PART 1

DRAWING AND DESIGN

Part 1 Drawing and design

1.1 Drawing as a figurative language
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1.1.2 Design function
1.1.3 Experiential representation

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1.2.2 The disclosure of imagery

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1.3.1 Classicism and provocation in the age of Enlightenment
1.3.2 The discreet charm of the 'picturesque' for the nineteenth-century bourgeoisie
1.3.3 Revaluation of the line in modern architecture

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1.4.2 A view on Wonderland: the digital photorealistic render

1.5 Creativity and design
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1.1 Drawing as a figurative language

The act of drawing has supported the architects' work since ancient times albeit its recorded existence in western culture only dates back to the thirteenth century and, even so, in rare survived documents.

From Renaissance, several crucial steps have characterised the historical development of this kind of graphic representation. The progress in optic science and further studies on perspective, new printing systems, the invention of photography, and finally the impressive advancement of computer technology has brought a constant evolution in the process of creating images. In the last century the concern on architectural illustration focused mainly on draftsmanship techniques to produce pictures that met the requirements of patrons. At the same time architectural illustration has also been the object of psychological studies focused on cognitive mechanisms of interaction between the various involved subjects, from designers to clients and lay public. Who makes architectural drawings and why? Which are the features of a graphical representation? Which is the audience meant to receive the message? Answers are closely linked to one another because the different subjects may have different needs and expectations (Smith Pierce, 1967).

Due to its communicative function, visual representation can be considered as a form of figurative language that translates mental concepts into images and, in doing so, allows a variety of interpretations. '*An architectural drawing is as much a prospective unfolding of future possibilities as it is a recovery of a particular history to whose intentions it testifies and whose limits it always challenges. In any case, a drawing is more than the shadow of an object, more than a pile of lines, more than a resignation to the inertia of convention*' (Libeskind, 1991) .

The difficulty to *read* or *watch* an architectural drawing according to predetermined criteria raised a debate about its empathetic nature. The literature on the subject reveals the difficulty in labelling a graphic work that, owing to its very nature as a mental product, can hardly be codified. However some scholars have studied architectural imagery focusing on its role in communication between designer and audience (de la Fuente Suárez, 2016; Hardenne, 1994; Meisenheimer, 1987; Oechslin, 1987; Seguí de la Riva, 1984).

1.1.1 The communicative function

In the 80s, when the architectural drawing was still considered a traditional and conventional image on paper, its three *communicative functions* have been emphasised: *representational, expressive and appellative* (Meisenheimer, 1987; Oechslin, 1987). If the drawing is part of the design process, it is considered a tool to represent an idea and to achieve the communication between architect, client and builders (*representational function*). Working drawings convey precise information to constructors, but to the layman they may just provide few clues about the appearance of a building. Throughout the history of architecture also other types of drawings have been developed and used. Whilst not strictly technical, they are aimed at a different types of communication. In them, the represented element, be it a town, a building, a room or an item of furniture, is highlighted by means of clever use of perspective, colours and other pictorial conventions. The object is rendered either alone or blended in an environment to make an appealing illustration. Such drawings may be addressed to clients, jury committees, professional partners and can be used together with the working drawings for competitions. Sometimes they represent something already built to be shown at exhibitions or published in books or magazines. A summary of the communicative function is shown in Fig. 1.1.

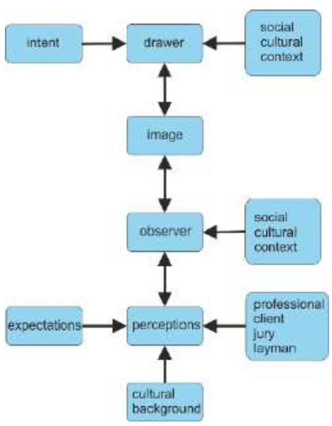

Figure 1.1. Flowchart about communication through the architectural image. Outer and inner elements affecting designer and observer.

These representations are most appreciated by the general public, because easier to understand and more captivating, hence deserving to be admired, even collected *(expressive function*). Finally, drawings may not be meant to provide any specific information but just to address the author's self: it may just be a means to fix on paper thoughts and uncertainties across the process of design. Also, images may be presented just to challenge the observer and stimulate his fantasy (*appellative function).* These drawings, though in appearance quite far from any practical application, do have relevant importance. As a matter of fact, there have been architects whose graphic work looks more significant and influential than their built architecture. Since the 60s some architects and designers have rediscovered the drawing as a tool for reflection and polemics, for artistic creation and social communication (Carpo, 2013; Riahi, 2017).

1.1.2 The design function

Since their introduction, computer graphics fostered new forms of virtual representation and created a novel relationship between the designer and his work. Envisaging a radical transformation of the architectural representation, since the 80s some scholars focused their attention on the graphic means traditionally used in the architectural practice. Schematically, J.P. Hardenne (Hardenne, 1994) identified five different types of *tools* that mark the work of an architect. The first tool is the freehand explorative drawing made to record buildings and sites, which enhances visual culture and understanding (*learning tool*). The second tool is the sketch that helps thinking and translates initial ideas in images (*conceptual tool*) (Fig.1.2). The third is represented by the preparatory drawing that allows going further into particulars (*representation tool*) (Fig.1.3). As fourth tool is proposed the technical drawing which shows each necessary detail (*communication tool*). Finally, the fifth tool is the perspective drawing which displays a realistic appearance of the project (*simulation tool*).

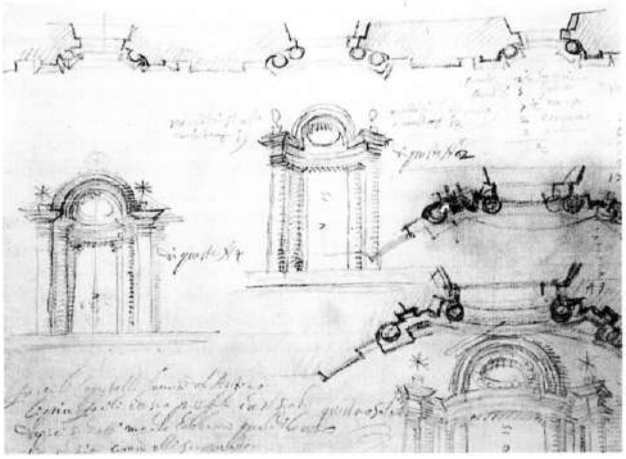

Figure 1.2. An example of *conceptual tool*. Francesco Borromini. Sketches for the windows of the Propaganda Fide Palace in Roma, c. 1647. Pencil on paper. Albertina, Vienna.

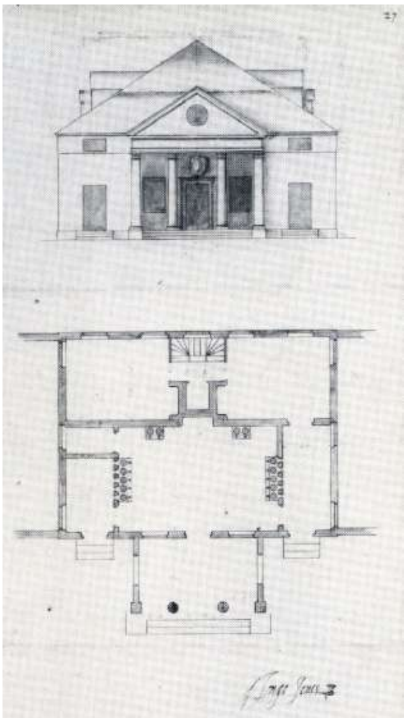

Figure 1. 3. An example of *representation tool*. Inigo Jones. Design for a brew-house, 1638 or later. Brown pen and grey wash. Drawings Collection of the R.I.B.A., London.

The age of CAD had opened unforeseen possibilities in the field of visual rendering and architects faced the challenge of a substantial change in their routine. Were computer graphics becoming an unavoidable tool in each working phase or could designers decide whether adopt the new technology or not? In those years the answer seemed to be a full acceptance or at least a strong inclination towards digital media for the three technical stages (3-4-5), leaving as optional the decision about the first two, which are the most creative in the design process (Hardenne, 1994).

This dichotomy still persists at least in the attitude of architects whose education and creativity were developed, before the advent of CAD, through the medium of drawing and model-making. B. Edwards explored how freehand drawing is employed in the design process by interviewing ten leading architects in the UK. The questions addressed to the architects dealt with the relationship between drawing and thinking, the type of drawing used at the different stages in the design process, the support provided by the drawing tool in problem solving and communication. All of them acknowledged the symbiotic relationship between thinking, drawing and designing on one side and the power of sketching to test and develop the initial design concept on the other. In spite of the wide use of digital cameras, most of them still keep either a personal sketchbook or notebook to collect precedents of interest and reinforce visual memory. They first make drawings and later on interact with CAD, usually considered a mechanical drawing and testing tool rather than a design aid. The findings of the research undertaken by Edwards suggest that freehand drawing remains paramount at the early stages of the design evolution. In this process hand drawing is the main tool employed. Early drawings contain the essence of architectural creativity, they are '*a kind of conversation acted out in line and often integrated with words, symbols and photographs to produce a kind of collage of design potential*'. '*CAD remains essentially a drafting, documenting and presentation tool*'. In addition, *'CAD glamorizes the image and provides at best a superficial impression of design quality*'. Its early use can undermine creative exploration and has a negative effect on architectural thought (Edwards, 2008).

B. Lawson, after having carried out a research in university contexts of three countries, maintains that he found '*examples of students combining impressive and* *convincing computer presentations with poor design…it is possible to put forward computer presentations that look attractive and even dazzling, that seem authoritative, while the architecture so represented is really quite awful*' (Lawson, 2002).

J. Pallasmaa, without disclaiming the digital techniques, emphasises the importance of handmade drawing and asserts: '*all students of design and architecture should first be taught to work with their internalised mental imagery and their hands before they are allowed to use the computer. In my opinion, the computer probably cannot do much harm after the student has learned to use his/her imagination, and has internalised the crucial process of embodying a design task. Without this mental internalisation, however, the computerised design process tends to turn into a purely retinal journey in which the student him/herself remains an outsider and observer without having built a vivid mental model of the conceived reality*' (Pallasmaa, 2009,p. 99).

S. Calatrava claims: '*The sketching and drawing I do for purely architectural purposes continues as intensely now as on the first day of my career. As far as my own experience is concerned, I sometimes begin a drawing with no preconceived problem to solve, with only the desire to use pencil on paper, and I make lines, tones and shapes with no conscious purpose. With drawing, you are always working with the same two instruments, your hand and your intuition; even if it seems you have no conscious aim, you're continually trying to solve a real construction problem. It is always the same process: sketch, repeat, change. I rely on continual drawing by hand because through very hard work, making hundreds of sketches, it is possible to arrive at a higher level…at a point where an idea becomes conscious and crystallized, and then a control and order begins to appear*' (Carrillo de Albornoz and Calatrava, 2018, p. 160).

1.1.3 Experiential representation

Another theory concerning architectural drawing, formulated by L.A. de la Fuente Suárez focuses on the interactive relation between architect and beholder based on their different experiential attitudes. Both the creative thinking of the architect and the physiological and cognitive mechanisms of the viewer are taken into consideration. An image on paper (or on screen) is not *reality* but the experience of an object, existent or non-existent, that is the representation of a mental concept by a person (creative process), to be perceived by other persons (interpretative process). From the point of view of the designer, exploratory drawings allow creating while representing. This type of representation is useful for generating ideas (*ideational representation*). The sketch is left open to interpretation, allowing new design alternatives to be explored. After the sketch, original ideas will be visualised by more specific and well-defined images to show clearly the appearance of the architectural artifact. *'However, to consider a representation as a resulting object is an incomplete approach, for this representational object is not a static or finished product, but something created to be experienced, i.e. an object capable of evoking the represented in the mind of the viewer*'. In the experiential representation two components, the *what* and the *how,* are related to the designer and the viewer: in the first case (production by the designer), what is represented and how is it represented? In the second case (reception by the viewer), what is experienced and how is it experienced? In the production process, the *what* originates from a *referent* (architectural space and elements) that the architect tries to represent in an image (referential representation). The *how* is the medium through which the object is delineated. In the reception process, a representation is interpreted as an object (*what*). The *how* is the particular interaction produced by the observer's encounter with the representation itself, which is a different experience compared to looking at a real object. Some other aspects of experiential representation are brought to attention by de la Fuente Suarez. A representation is *selective*, i.e. it just encompasses some features of the object, not only because it is impossible to render all aspects of a personal experience, but also because the architect is interested to give prominence to elements or qualities considered more relevant and wants to direct the beholder's attention to them (*directive representation*). A representation is not limited to visualisation, other experiences can be part of it. '*By the term architectural experiences we refer to the phenomena that buildings can cause in humans, i.e. those arising from the interaction between our senses, body and mind, and the building.*

Such phenomena include the sensory encounter with architectural works –e.g. tactile, auditory, visual etc.-, the perception of depth and lighting, our movements and activities in space, the meanings, thoughts and emotions that architecture produces in us' (de la Fuente Suárez, 2016) .

1.2 The drawing and the audience

The drawing can just be an inner monologue by the architect, an expression of mental processing, yet the architectural illustration also represents a visual dialogue with other people. Leaving aside the working drawings meant for the architect's staff and builders, in other kinds of imagery the drawer seeks to meet the audience's demands and expectations. The perspective has been the first tool to render an object in its spatial dimension and has been steadily used until today. In addition, the diffusion of innovative methods of reproduction has been an enormous boost to disseminating architectural illustrations, praised by artists, collectors and laymen. The great success of drawing prints in modern history can only be compared to the widespread imagery through the web and other mass media in our digital age.

1.2.1 The need for three-dimensionality

Until the fourteenth century, building practices were mainly empirical, being based upon well established traditions and knowledge of geometric rules handed on through generations by itinerant master craftsmen. Drawings were not used to project a building in its wholeness, in their stead wooden models were made to represent the general structure and fairly often details were designed on site. Medieval anonymous drawings were just templates, often annotated for direct use on the construction site. In erecting Gothic cathedrals, masons were building the house of God, the Architect of the Universe. Their earthly work was strictly linked with theological and cosmological implications, thus the written paper was considered a language intended only for initiated.

The fifteenth century marked the beginning of a new conception of architecture as a liberal art separated from the builder's craft and related to innovative theories about *vision* and *image*. Studies on the human eye and its *modus perspiciendi were performed*, which was both a way of watching an object and a way of understanding its inner essence. A key role in these researches was played by the perspective that became a topic in the debates, due to its importance as a technical device to obtain a tridimensional representation. Images of buildings had been previously depicted by painters. It suffices to mention urban landscapes by Giotto and Lorenzetti and, going back in time, by roman artists (Fig.1.4), but the approach to the representation was still empirical. Scientific studies to improve the perspectival representation were carried out both by architects and by painters particularly versed in mathematics, such as Piero della Francesca (Fig. 1.5) and A. Durer.

Figure 1.4. Roman fresco in the villa of Publius Fannius Synistor. First century b.c. Metropolitan Museum of Art, New York.

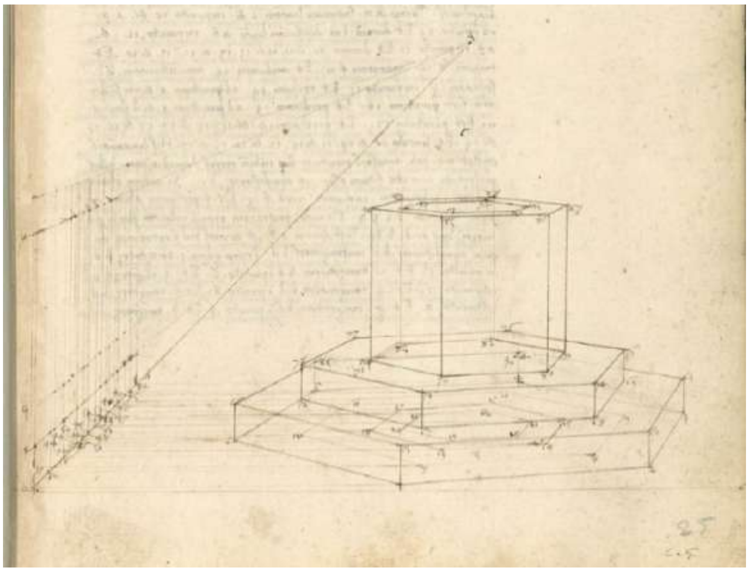

Figure 1.5. Piero della Francesca, 'De prospectiva pingendi', ms. 616, c. 1475. Bibliothèque Municipale, Bordeaux.

Filippo Brunelleschi and Leon Battista Alberti were the first architects to address attention to the geometric system that was regulating the visual world and to the mechanisms of perspective. Their theories, first applied to the art of painting, '*were associated with architecture primarily because the regular geometry of architectural subjects enable perspective depth to appear, and less obviously because of the quasi-magical generative power attributed to mathematics and proportionality in revealing the secret structure of the cosmos*' (Pérez-Gómez and Pelletier, 2000, p. 23). Alberti introduced the notion of architectural design as an intellectual product with the meaning of a rigorous scientific graphic representation. In his treatise 'De re aedificatoria' Alberti wrote that architecture is made of drawing (*lineamenti*) and building (*structura*). The architectural drawing consists in finding a precise rational method to fit and link together lines and angles in order to render the intended building in its completeness (Alberti, 1966, p.18) .Further on, Alberti comments on the difference between the geometrical bi-dimensional drawings of the architect with plans and elevation and representations by painters aimed at conveying the live illusion of three-dimensional objects coming out of the canvas: '*Between the* *graphic representation of the painter and that of the architect, there is this difference, that the painter by the exactness of his shades and the foreshortening of lines and angles endeavours to make the figures seem to rise from the canvas, whereas the architect, without shading, brings his projected building into relief by designing the plan and visualises the elevations by drawing exact lines and angles; thus he will have his work valued not by the apparent perspective (apparentibus visis) but by rational measurable dimensions (certis ratisque dimensionibus)*' (Alberti, 1966, p. 98). Though Alberti advised architects against the use of perspective, the path was now open to new illustration techniques, not only based upon geometry but also on pictorial methods.

Raffaello was aware that combining technical *lineamenti* with perspective drawings was an effective means to make more visible and intelligible a building still in the design phase. In his letter to Pope Leone X in 1519 Raffaello claimed *'And, in order to satisfy even more thoroughly the desire of those who love to see and fully understand all the things that will be drawn, we have, in addition to the three methods of architecture proposed and mentioned above [plan, elevation, section], also drawn in perspective some buildings which they seem to seek so that the eyes can see and judge the gracefulness of that resemblance revealed to them by the beautiful proportion and symmetry of the buildings, which do not appear in the design of those that are architecturally measured ... And, although this way of drawing in perspective is typical of the painter, it is also suitable for the architect. Because, just as the understanding of the architecture deserves to be known to the painter to make well-measured ornaments with their proportion, at the same time the architect has to know the perspective because with that technique he better imagines the whole building provided with his ornaments*' (De Vecchi, 1995, p. 195, translation by the author).

Also the architect Jacopo Barozzi da Vignola asserted the need for perspective drawing to better understand a drawing or a design in its spatial consistency: '*An architect is someone who must possess at least these four Sciences, namely Grammar, Arithmetic, Geometry and Perspective ... and who is also inclined* *to always study, and invent*' (Barozzi da Vignola, 1682) (translation by the author) (Fig. 1.6).

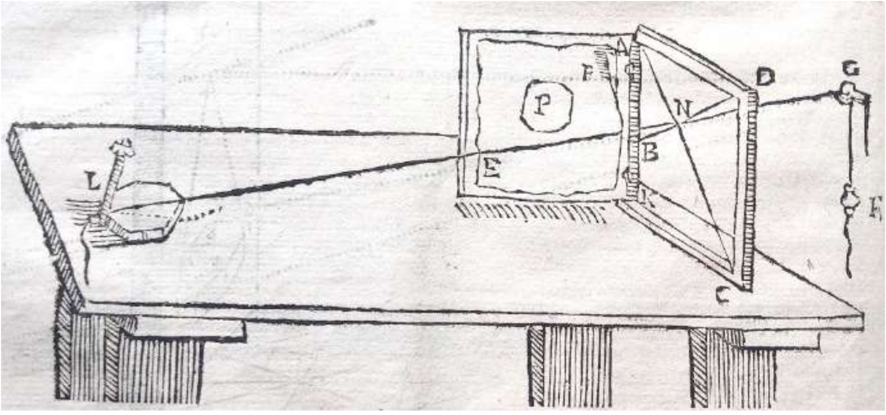

Figure 1.6. Jacopo Barozzi da Vignola, 'Le Due Regole della Prospettiva Pratica'. A perspectival device. Bologna, G. Longhi Publisher, 1682.

1.2.2 The disclosure of imagery

In addition to the studies on perspective, in those years another phenomenon was having a huge impact on handmade drawings: the diffusion of printing techniques made it possible the dissemination of images that so far were only visible to a small circle of people. If the perspective allowed a greater understanding of a design, the printing promoted this new understanding among a wide range of the public. The architect and painter Francesco di Giorgio Martini pioneered the use of supplementing the text with images. In his 'Trattato di architettura, ingegneria e arte militare', he supported his writing with an exceptional number of illustrations (Fig. 1.7). Martini considered this method a useful tool for *i diligenti e curiosi architettori* to translate an idea into an accurate project. He '*recognized the potential power of drawing beyond mere illustration and used drawing both as a creative mode of inquiry and a vehicle for communication*'. He '*promoted the primacy of draftsmanship explicitly and effectively and by doing so paved the way for an extensive engagement with drawig by the generation who followed*' (Riahi, 2016, p. 1)

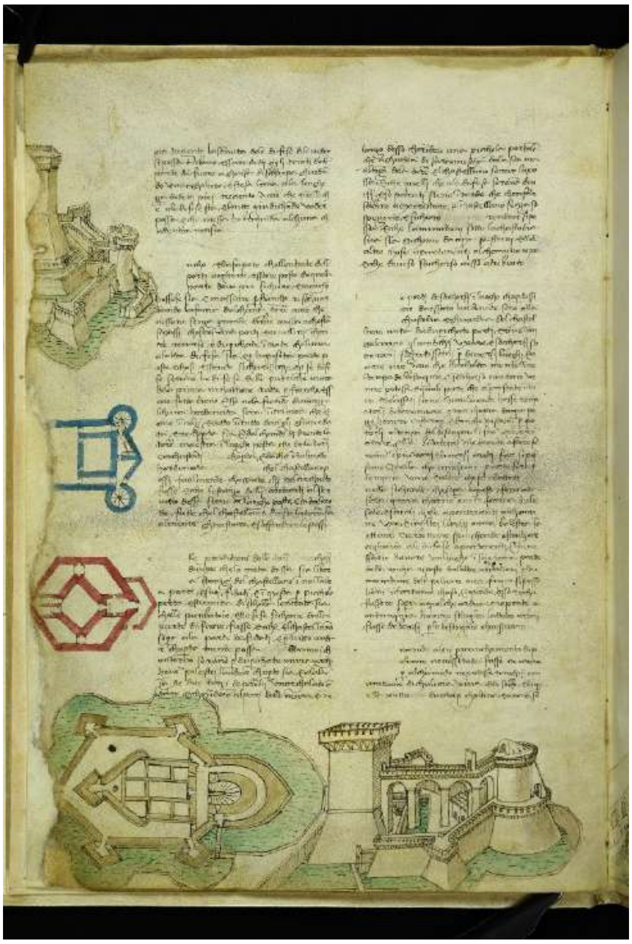

Figure 1.7. Francesco di Giorgio Martini. 'Trattato di architettura civile e militare'. Codex Ashburnham 361, c. 1490. Biblioteca Medicea Laurenziana, Firenze.

During the sixteenth century engraving techniques, perfected by printmakers and publishers who had undertaken successfully large enterprises especially in northern Europe, allowed the dissemination of high quality images at affordable costs. New types of drawing were created that met expectations and tastes of an unprecedentedly vast number of purchasers: architects, painters, collectors, bibliophiles and art dealers who showed interest in printed architecture for different professional reasons. This new availability of edited illustrations paved the way for innovative architectural imagery. The treatises of Sebastiano Serlio and Andrea Palladio became influential landmarks throughout Europe. These works, meant to be edited, disseminated professional experience and creative design by means of rich kits of high quality drawings that became a collective heritage. Serlio was the first one to have his drawings printed to supplement the text. Alberti's unillustrated treatise was written in Latin and destined only for the humanistic cultural élite. Serlio wrote in Italian and some of his treatise books were published also in French. Whereas his general intent was educating the taste for beauty, his practical task was meeting the needs of architects and craftsmen by means of technical information, historical data and project templates. Copies of Serlio's treatise were spread out in France, Germany, the Netherlands and Britain, and famous architects had a copy in their libraries. The second book is about the theory of perspective and the design of scenes in which perspective is essential. Serlio developed studies on the theatrical setting already outlined by Vitruvius, that became influential during the following centuries (Fig. 1.8).

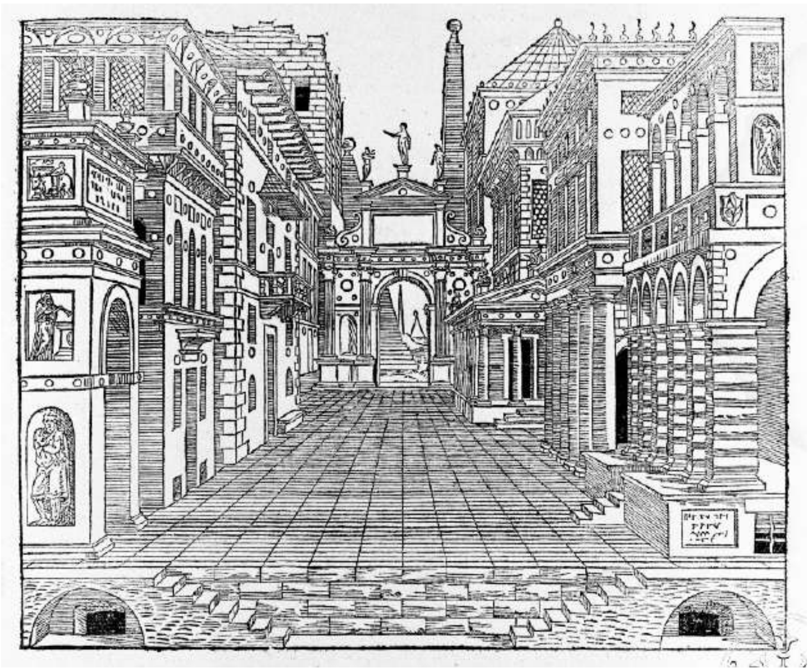

Figure 1.8. Sebastiano Serlio, 'I sette libri dell'Architettura', second book: On perspective, the tragic stage. First edition: Venezia, P. de Nicolini de Sabbio Publisher, 1551.

Palladio, besides information and instruction to the practicing architects by illustrating his own methods and proven solutions, presents his drawings of ancient monuments that he had the opportunity to admire on previous journeys to Rome. '*Ridurre in disegno*' (converting/translating into drawings/representing with drawings) was the most suitable method to '*comprendere*' (understand) in its completeness a monument or a building, after having measured it '*minutissimamente con somma diligenza*' (in the smallest details with great diligence). (Palladio, 1570) (introduction to the first book). This drawing, though an imaginative rendering, shows meticulous attention to the representation and extreme precision over details. Palladio never drew in perspective, preferring the more accurate methods of plan, elevation and section, though his skillful use of chiaroscuro still gives a remarkable effect of three-dimensionality (Fig. 1.9).

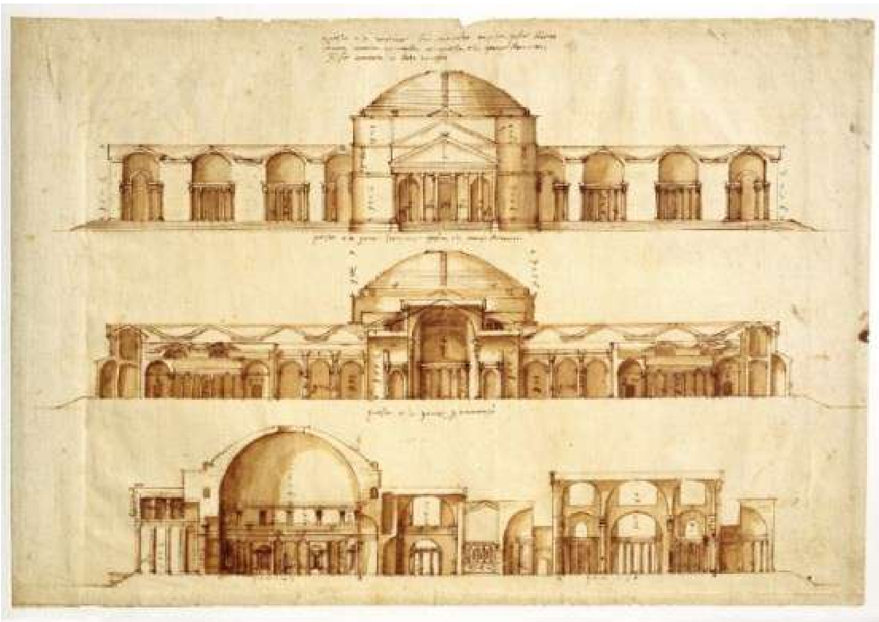

Figure 1.9. Andrea Palladio. Fancy restoration of the Agrippa's Terme in Rome, gone to ruin. Sections, c. 1550. Drawings Collection of the R.I.B.A., London.

The graphic work by the Dutch architect, painter and print designer Hans Vredeman de Vries, an estimator of Serlio's work, became a reference chiefly for painters of cityscapes and for makers of ephemeral urban decorations. His printed drawings, a sort of unprecedented guidebook for artists, displayed perspective sequences of ideal contemporary architecture as patterns to be admired by an educated audience and to be copied as starting points for further experimental representations. Vredeman's architectural images usually were devoid of characters, the addition of human figures was usually part of collaboration with other artists, a common practice in that time as the depiction of people, not always necessary, was a secondary accessory that could increase the marketability of a painting (Heuer, 2009) (Fig. 1.10).

Figure 1.10. Hans Vredeman de Vries. 'Scenographiae, sive perspectivae', Etching, 1560. Albertina, Vienna.

Despite their large appreciation, printed architectural images were not without criticism. The Italian theorist and painter G.P. Lomazzo warned his readers about the risk of mental laziness due to the increased availability of reproducible templates. In his opinion this new habit improved the art of building by practice and plagiarism, not by invention. Serlio's prints, he claimed, turned '*more construction workers into architects than he had hairs on his beard*'. Creativity had to remain a prerogative of '*expert designers who have their hand ready to outline and represent what they conceive and realise in their mind'* (Lomazzo, 1585, p. 407, translation by the author). These fears were fortunately disproved. Architects, at least most of them, continued to show their creativity by handmade drawings, using printed images only to disseminate defined personal outcomes which were intended to be admired more than to be copied. What Lomazzo didn't say, or couldn't envisage, was that the very notion of graphic work was about to undergo a radical change. With regard to architectural drawings, the visualisation of an idea or the illustration of a building was no more a single representation of a work of art. The uniqueness gave way to reproducibility: the charm of a handmade drawing could be appreciated by a few, whereas its copy could be looked at by a much larger audience. The published illustrations were an outstanding means to bring remains of the classical age and famous buildings to the attention of interested people. Some Flemish draftsmen made a specialty by depicting views of art cities intended for sale. Buildings, streets and squares were accurately portrayed using perspective to render them more realistic and easy to understand. Such renderings were appreciated by educated travellers as souvenirs of their trips, or else by the lay public curious of images from foreign countries. The architect and engraver Lievin Cruyl, during his long stay in Rome, masterly depicted scenes of daily life set in the most representative places of the city. Some of them were collected in a book dedicated to Pope Alexander VII, who had promoted a large-scale urban renewal. The descriptive purpose is particularly evident in the use of captions helping the reader to identify the most remarkable monuments. The study of peculiar perspectives and attention to architectural features did not prevent Cruyl from adding human figures of different social conditions. In this kind of imagery the architectural representation, even though accurately performed, appears subdued to descriptive effects and anticipates the widespread success of the pictorial movement called *Vedutismo*. In figure 1.11 Cruyl renders the overview of Piazza Navona more appealing by drawings the buildings reflected on the wet ground, a successful ‘trick’ that will be replicated by several architectural illustrators in the future years.

Figure 1.11. Lievin Cruyl. Perspective view of the ‘Forus Agonalis’, in ‘Prospectus locorum urbis Romae insignium’. Print from a drawing in pen, brown ink, brush and grey wash. M. G. De Rossi Publisher, Roma, 1666. Universiteitsbibliotheek, Gent.

Voltaire wrote that the 18th century was not favorable to young architects who wanted to practice. Unlike other artists, gifted architects had rare opportunities to display their skills, they could raise important buildings only when asked by rich clients. Thus their talent was often wasted. One of these missed architects was Giovanni Battista Piranesi who claimed: *‘Since an architect nowadays has no hope to exercise his profession, I have nothing left, like other modern architects, but explaining my ideas by means of drawings’* (Piranesi, 1745) (translation by the author). He had a central role in devising new types of representation, asserting their autonomy from the design process. His views of ancient Rome, printed through the complex technique of etching, stood out for the extraordinary visual relief of the monuments they represented, conveyed thanks to the unconventional use of impressive perspectives. His figurative language had no precedents, merging pictorial effects with the spatial dynamics of stage design tradition. From the Roman printing workshop of Piranesi, attended by foreign guests of the French Academy and by the cosmopolitan society engaged in the Grand Tour, new prolific ideas spread all over Europe. Architectural representation became a genre in its own right, which offered innovative suggestions rising from painting and scenography. Piranesi's series of prints on Rome and its surroundings combined archeological accuracy with a profound knowledge of Roman architecture and building materials. Ancient monuments were faithfully represented and the atmosphere of decay was rendered in an exquisitely evocative way. Piranesi intended to preserve, at least in the graphical representation, an invaluable heritage that he considered superior to Greek culture. His illustrations influenced other architects both promoting ancient architecture and inspiring more flexible techniques of representation. Besides affecting architectural tastes towards a new classicism, his drawings representing monuments in ruins inspired contemporary artists and illustrators for years to come (Fig. 1.12).

1.3 The language of the line and the language of the perspective

From the sixteenth century onwards, the dichotomy already pointed out by Alberti between the representation of an idea through lines and its realistic image through perspective was still a topic of discussion among architecture theorists. In daily practice or in their essays intended for publication, architects found that these two kinds of visual language could offer new opportunities in the field of communication, either to represent real projects or fanciful proposals. Side by side or merged together these drawings were tools for illustrating their thoughts. Sometimes they gained the status of true works of art and became cultural icons.

Figure 1.12. Giovanni Battista Piranesi. The Campus Martius of Ancient Rome: remains of the Portico di Marco Filippo. Etching, 1762. Istituto Centrale per la Grafica, Roma.

1.3.1 Classicism and provocation in the age of Enlightenment

L'Académie d'Architecture, then École des Beaux-Arts, founded by King Louis XIV, was a French institution that had a leading role in coding the features of architectural representation throughout Europe. The academicians developed and imposed, especially for utilitarian buildings, a style almost exclusively based upon the Roman and Greek classical orders. Future architects were trained on the traditional working drawings, i.e. plans, elevations and sections, and the use of perspective was unusual. The only permissions to pictorial effects were the shading of elevation drawings with monochrome washes and the colouring of some details. The so-called 'presentation drawings' required a high level of precision in making. In 1832 the French art theorist A. C. Quatremère de Quincy in his *Dictionnaire historique d'architecture* remarked as extremely important that in representing buildings each drawing had to be '*rendu*', i.e. perfected in its details, because '*the drawing shows the artist's skill and his care in illustrating as faithfully as possible all the parts of his work*' (Vernes, 1984, p28). The perspective was gradually introduced among the teaching courses of the Académie to help the architect '*make* *prominent his design, arousing in his clients a joy and excitement before the actual construction*'. Whilst the ground plan conveyed the accuracy of the design, the elevations represented the outer appearance of the building and could be rendered with techniques matching the taste of the beholder and stimulating his imagination. Thus it was taken for granted that the interest of the lay public for architecture focused on the outer appearance of the building and its relationship with the surrounding environment. The aim of the drawing, not too technical nor pictorial, was to '*charm with discretion and inform without being dull'* (Vernes, 1984, p. 28).

Despite the academic instructions to only use '*dry and severe'* representations, some architects tried to render their drawings more appealing when intended to the lay public. Claude-Nicolas Ledoux, when designing the utopic city of Chaux, made a series of drawings out of the ordinary standards. In order to appeal to the audience he used a visual strategy that strikingly anticipated the photomontage technique. He fit the image of his projected buildings into realistically painted landscapes or cityscapes that served as background settings.

Figure 1.13. Claude-Nicolas Ledoux, The ideal city of Chaux. House of the surveyors of the Loue river. Engraving, 1804. Fisher Fine Arts Library, University of Pennsylvania, Philadelphia.

The familiar view of vegetation, acting people and animals made the design easier to understand and to accept as a possible reality by untrained onlookers (Fig. 1.13). The drawings of this ideal city became part of the Ledoux's treatise 'L'architecture considérée sous le rapport de l'art, del moeurs et de la législation' and, after its publication, helped to make him known as a pioneering architect in visual representation.

New techniques for astonishing drawings were offered by the Bibienas' studies, which introduced innovative methods of perspective in stage design amplifying the boundaries of imaginary spaces. The *scena* or *veduta per angolo* '*displaced the focal point of the composition out of the audience's sight by replacing the primary vanishing point – traditionally on the central axis of the baroque stage – with a two-point perspective, so as to create a greater illusion of reality… The basic pattern of the scena per angolo was based either on a V-shaped plan, with its acute angle pointing toward the audience, or on an X-shaped distribution of intersecting arcades that spread simultaneously forward toward the proscenium arch and backward through receding rows of columns. Thus, the audience…was drawn into the perspective illusion of scenery*' (Pérez-Gómez and Pelletier, 2000, p. 207) (Fig. 1.14).

The dazing scenes created by the Bibienas had a great influence on graphic expression, mostly as a means to explore, in an unconventional way, the indefinite limits between reality and illusion, buildable and unbuildable. A renowned specimen of this kind of drawing was Piranesi's publication *Carceri di Invenzione*. It was his most famous set of printings and perhaps the most extraordinary of his time. He investigates new possibilities of representation deconstructing the homogeneous space of the traditional perspective. Images represent in a compelling rhythm the same scenery: wide vaults encompassed by massive gloomy walls, intersected and crossed by the most unlikely perspectival structures. The artist creates tangles of stairways, arches and bridges that emerge from disconcerting depths, in sharp contrast of light and dark, and are projected beyond the edge of the drawing toward the onlooker (Wilton-Ely, 1978) (Fig. 1.15).

Figure 1.14. Giuseppe Galli Bibiena, Scenographic fantasy. Engraving, 1740. Albertina, Vienna.

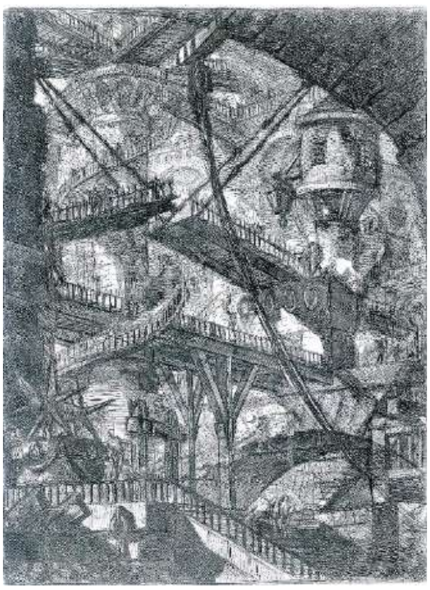

Figure 1.15. Giovanni Battista Piranesi, Carceri di Invenzione: the Drawbridge, c. 1750. First edition: Bouchard Publisher, Roma.

The *Carceri* imagery has been influential throughout Europe and even today they astonish the observer. They have given way to graphic experiments on optical deception and ambiguous perception by architects and painters, until the unsettling perspectives by Surrealist and Metaphysic painters. Graphic signs in Piranesi's drawings create a sort of new iconographic language that intentionally defies routine conventions. A similarity has been found between Piranesi and Libeskind. Like the Italian artist, Libeskind explores through a series of drawings the meanings of architecture by transgressing its limits. These images seem to challenge the visual perception of the observer who is seized by different, contradictory hints at once (Meisenheimer, 1987; Oechslin, 1981). According to Libeskind's words, '*My drawings and projects are a critique of the venerable and now exhausted virtuosity of the "Language of Architecture". For me…it has become a false –albeit well informed- rhetorical device*'. '*My own work is concerned with the specific meaning of a metaphorical, fictional and artificial construction -architecture- and its capacity to reveal the truth of reality*' (Libeskind, 1991) (Fig. 1.16).

Figure 1.16. Daniel Libeskind, Berlin City Edge, 1987, Ink on paper. Museum of Modern Art, New York.

1.3.2 The discreet charm of the "picturesque" for the nineteenth-century bourgeoisie

The French notion of *dessin rendu* was adopted in Britain, where realistic representation in the architectural project was illustrated by means of *renders*. In these drawings the 'artistic' effects were emphasized, more than in other countries, by making use of perspective and of pictorial devices. One possible reason for the sudden development of this kind of illustration may have been the foundation of the London Royal Academy of Arts in 1768. In the annual exhibition of works by contemporary artists, architects had the opportunity to show their designs to a larger cultivated audience. They may have realised the advantage of adopting an immediately comprehensible and appealing method of representation rather than relying upon the dry perfection of geometrical drawings. The landscape painting, particularly appreciated in those times, may have been another reason for the shifting towards the depiction of a building not as an object of its own, but rather as an artefact inserted in a natural context. The environment became just than the necessary counterpart wherewith a building must dialogue and a basic element for the architect to consider. In his first lecture given as Professor of Architecture at the Royal Academy in 1809, John Soane announced that *'The Student in Architecture ... must be familiar with the use of the Pencil and must not be satisfied with Geometrical delineation, for the real effect of a Composition can only be correctly shown by Perspective representation'* (Stamp, 1982, p. 28). Soane was the affectionate patron and employer of Joseph Gandy, a brilliant illustrator whose frustrated career as a practicing architect was balanced by the reputation he had reached as a master of pictorial architecture. His attractive watercolours had been shown annually at the Royal Academy for thirty years. '*Gandy's renderings of Soane's designs were distinctly visionary in presentation and richly connotative in imagery…Gandy strove to combine the pictorial drama of the Piranesian tradition with the sensitive landscape aesthetic of contemporary English watercolor painting*' (Lukacher, 1987). Gandy shared Soane's discomfort about the ordinary standard of English architecture and his aspiration to raise it to an outstanding level, similar to Roman magnificence. In Gandy's drawings visual effects of ancient ruins, indeterminate vastness and grandiosity were predominant, where the chiaroscuro played a spectacular role to create an uncanny atmosphere, that met the aesthetic aspirations of Romanticism and Sublime. A challenging and nontraditional work was the depiction of the Bank of England, a huge and articulated complex of buildings designed by Soane and erected in London between 1790 and 1827. In Soane's 1830 Academy exhibit, Gandy rendered the newly built Bank of England as a surreal vision of ruins of great visive impact (Fig. 1. 17). His aerial vista, as a display of future decay, included the plan, section and perspective on a single sheet. "*The structural innovations, spatial sequencing and interior distribution…are made visible…The overall effect of the rendering is that of a storm-streaked ruinscape with architectural debris and vegetation encroaching from the corner*" (Lukacher, 1987). This representation surprisingly anticipated the historical fate of the Bank erected by Soane: less than a century later most of it was destined for demolition.

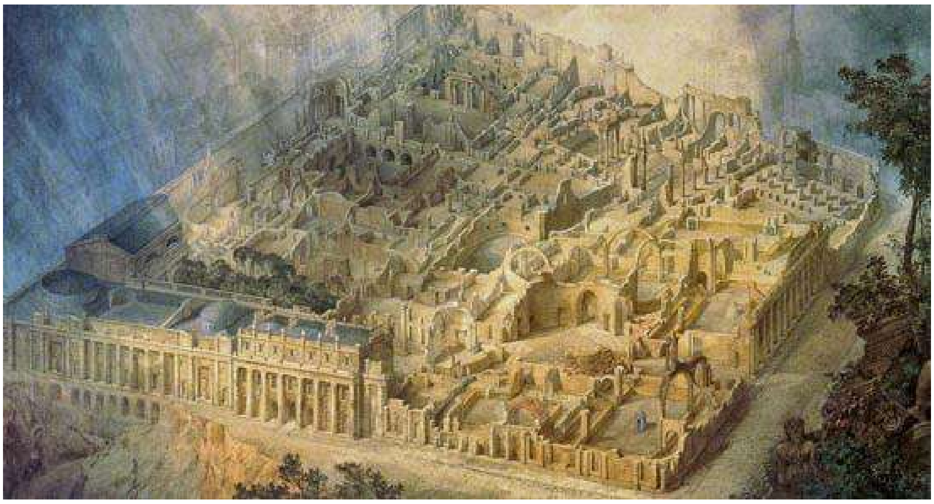

Figure 1.17. John Soane, A Bird's Eye View of the Bank of England in ruins, c. 1830. Watercolour on paper by Joseph Gandy. Sir J. Soane's Museum, London.

Gandy's renderings did not always arise unconditional admiration, sometimes he had to bear distrust and criticism by the architectural press, which usually preferred the technical accuracy to the artistic visions. Nevertheless the spell of architectural images depicting future ruins is long lasting for its implications on the corruptibility of human history and the vulnerability of architecture as a living structure destined to an ineluctable end. Even A. Isozaki has rendered his Tsukuba Center, a multifunctional space built in the 80s near Tokio, as a square enclosed by ruins, *"in order to imbue it with a fictional life beyond the building's conventional existence*" (Lim, 2013) (Fig. 1.18).

Figure 1.18. Arata Isozaki, Tsukuba Center Buildings in ruins. Tsukuba Science City, Ibaraki Prefecture, Japan, c. 1983. Mixed technique and watercolour. https://entirelandscapes.space/Tsukuba-Centre.

Some British architects took a further step in the realm of fantasy, by creating imaginative drawings of fictitious architectures and urban landscapes. It was not a play in itself, but a kind of imagery that could have different purposes: to illustrate a cultural atmosphere, clarify personal ideas, communicate utopic dreams, even satirise their own times. The lack of cultural and spiritual connotations of eclecticism had caused a crisis of meaning and style in contemporary design. Charles Robert Cockerell in his academic lectures remarked sarcastically that '*the art has reached its ne plus ultra by the confusion of all ages'* (Lever and Richardson, 1984). In his drawing (Fig. 1.19) Cockerell depicts an imaginary city where products of all civilizations are represented, monuments of ancient Babylonia and Egypt, Greek and

Roman masterpieces, Gothic and Renaissance buildings. Monuments are recognizable and the mixing of styles and countries puzzles the observer. Just a dream or a message?

Figure 1.19. Charles R. Cockerell. 'The Professor's Dream'. Pen and watercolour. 1849. Royal Academy of Arts, London.

Pictorial perspective drawings flourished in Britain to a much greater extent than in any other country; this kind of representation achieved considerable virtuosity when performed by prominent architects and talented illustrators. These detailed renders, sometimes juxtaposed to working drawings, could be used, as in figure 1.20, to bring attention to the quality of the materials. Nevertheless in too many cases pictorial effects, commonly accepted to a certain degree, had overwhelmed the technical language, becoming an impediment to the correct perception of the project by builders, jury committees and general audience. The authoritative journal *The Builder* had expressed reservations on the choices made by the judges during some competitions, due to the presentation of *'showy drawings, or anything rather than design and constructive skill*' (The Builder, 1857).

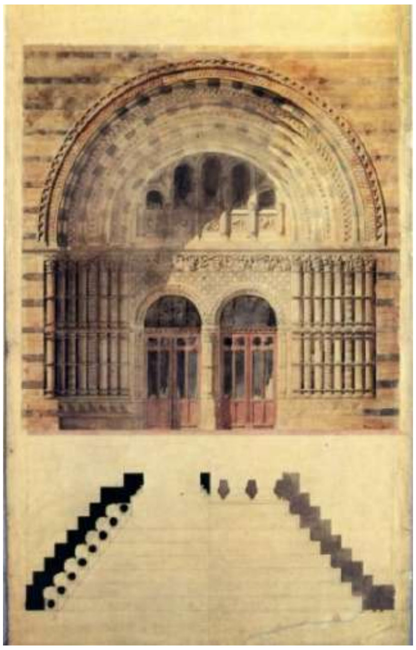

Figure 1.20. Alfred Waterhouse. Design for the principal door of the Natural History Museum, London. Plan and elevation, c. 1872. Pen and watercolour. Drawings Collection of the R.I.B.A., London..

The shifting towards the 'picturesque', typical of Victorian times, frequently turned architectural illustrations into pictures to hang in the bourgeois parlor as objects of furniture. Prominent British architects couldn't do without three-dimensional imagery as well as technical drawings. Edwin Lutyens, while asserting in 1897: '*A working drawing is merely a letter to a builder telling him precisely what is required of him, and not a picture wherewith to charm an idiotic client*', kept on producing fine pictorial and realistic illustrations for customers, competitions and exhibitions (Lever and Richardson, 1984).

1.3.3 Revaluation of the line in modern architecture

The period between the 19th and 20th century was a time of innovative and radical changes in all arts: in the span of a few decades, avant-garde movements marked a definite break against traditional styles and new modes flourished in Europe and America, often influenced by the contemporary painting. Meanwhile, the graphic language of architecture underwent a deep metamorphosis, changing into different trends. The *Art Nouveau* Movement represented an answer to the negative consequences of industrialisation and proposed a revaluation of Nature, regarded as a dynamic and vital force. Inspired by botanical forms and Japanese prints, graphic arts privileged the use of the line traced in flowing curves to perform stylized ornate decorations in bright colours. Architects often designed furniture in the new style to accompany their building projects. A transition towards more geometric forms was marked by the *Art Deco* Movement which preferred straight lines and simple shapes both in architecture and in all ornamental aspects related to artistic creation.

Instead of smooth changes, the Italian *Futurismo* made a sensational disruption from the tradition in all arts. In 1914 the *Manifesto dell'Architettura Futurista* by Antonio Sant'Elia was a strong charge against architectural conventional styles, from classicism to gothic, from eclecticism to the other contemporary movements in Europe and America. Sant'Elia claimed: '*The problem posed in Futurist architecture is …in determining new forms, new lines, a new harmony of profiles and volumes, an architecture whose reason for existence can be found exclusively in the conditions of modern life…We must invent and rebuild the Futurist city like an immense and tumultuous construction site, vital and dynamic in every part of his, and the Futurist house must be like a gigantic machine*' (Sartoris, 1993, p. 88, translation by the author).

The illustrations made by Futurist architects had an enormous impact on modern representation. The very concept of *line*, essential for their creating architecture, underlies new graphic expressions. In their manifesto they asserted: '*Oblique and elliptic lines are dynamic, and by their very nature possess an emotional power stronger than perpendiculars and horizontals…no integral, dynamic architecture can exist apart from them'* (Sartoris, 1993, p. 90, translation by the author). Vertical lines are the true connotation of tall buildings and one of the features of Futurist imagery. Occasionally these drawings, where the line is the prevailing element, are vividly coloured since in Futurist aesthetics the '*violent* *colour*' of the building material has a decorative value. Their visual impact produces an effect of reality on the illusory design and one could say that they anticipate the digital renders (Fig. 1.21).

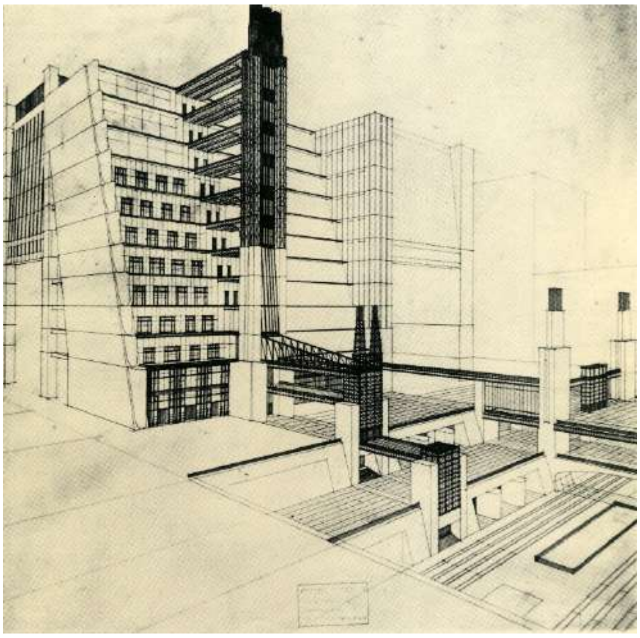

Figure 1.21. Antonio Sant'Elia. 'The New City: study for a staircase house with lifts upon four road levels', 1914. Black ink and pencil on paper. Collezione Paride Accetti, Milano.

Futurists' ideas on the representation of a building or a cityscape were developed after the first world war by architects and designers of various countries who shared the emphasis on pure lines and geometrical surfaces, without indulging in decorative forms. Unconventional techniques of representation were explored by architects themselves not simply to present an explanatory illustration of a building but to try new visual tools for a better understanding of architectural design.

The Netherlands-based art Movement De Stijl promoted pure abstraction of form and colour instead of pictorial features, both in architecture and painting. The reality was not so much a visual perception of outward appearance as the deep insight of the essential design principles.: straight horizontal and vertical lines bordering the space and primary colours underlining the surfaces. The Dutch architect Gerrit Rietveld chose axonometry to explain the complex relationship between form and space of the Schroeder House (Fig. 1.22). This technique, while maintaining a geometrical accuracy, draws attention to the dynamic rhythms of the composition. Though traditionally the observer focuses on the exterior appearance of a building, Rietveld introduces transparency to consent vision beyond walls and spatial depth perception. The drawing gives the illusion of a centrifugal space where planes and walls are visually projected beyond the surface of the image. According to the statements of De Stijl Manifesto, " *The subdivision of the functional spaces is strictly determined by rectangular planes, which possess no individual forms in themselves…they can be imagined extended into infinity, thereby forming a system of coordinates…From this it follows that the planes possess a direct tensile relationship with exterior space*". Basic colours outline the relationship between architectural elements and interior furnishings of the house (Luscombe, 2013). One cannot fail to notice the visual similarity with Mondrian paintings.

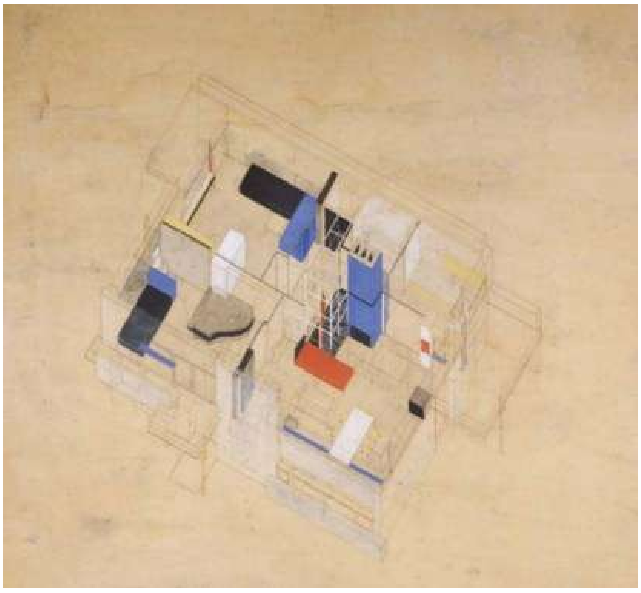

Figure 1.22. Gerrit Rietveld. Schroeder House, Utrecht. Coloured axonometric on grey cardboard. c. 1924. Centraal Museum, Utrecht.

Avant-garde and Modernism shared the revaluation of the line as the primary element in architectural drawings since the line was acknowledged as the leading sign during the design process and also a necessary means to convey the final idea to an external audience. They expressed a clear mistrust and a dismissive attitude towards realistic representation as a misleading means of communication (Fig. 1.23).

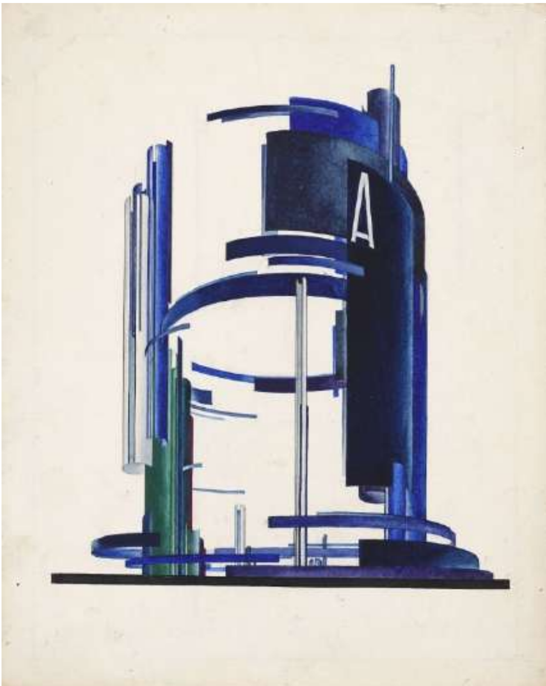

Figure 1.23. Yacov Chernikhov, Architectural fantasy. Set design with concave surfaces. Coloured ink on paper. c.1927. Musée de Beaux Arts, Paris.

This criticism against pictorial drawings is evident in Le Corbusier's thought. In his manifesto, 'Vers une architecture', first edited in 1923 he claimed: '*The whole structure rises from its base and is developed in accordance with a rule which is written on the ground in the plan: noble forms, variety of form, unity of the geometric principle'* (Le Corbusier, 1986, p. 48). *The regulating line is a satisfaction of a spiritual order which leads to the pursuit of ingenious and harmonious relations…The regulating line brings in this tangible form of mathematics which* *gives the reassuring perception of order. The choice of a regulating line fixes the fundamental geometry of the work…it is one of the vital operations of architecture*' (Le Corbusier, 1986, p. 75) His statements remind Alberti's assertion on *lineamenti* as unique graphic tools.

This well-known drawing by Le Corbusier shows a wall of Villa Stein *"as a paper-thin plane, like a stage flat from which windows might have been cut with a scissors, as Frank Lloyd Right observed. But the openings are rendered as opaque lavender patches - not the most obvious way of indicating glass - and the sky, essential to this drawing, is like a blue wall on which Le Corbusier has hung a painting"* (Drexler, 1984, p. 24). In this image any reference to the environment is removed so that the observer can see the house as an object of thought and concentrate on its formal qualities. The drawing is reduced to essential forms, reminding Purist theories. The colour on the flat surface does not conceal the harmony and proportion between each part and the whole. The villa's structure exemplifies Le Corbusier's mathematical theory based on the *Modulor* system and the *Golden section* application. (Fig. 1.24).

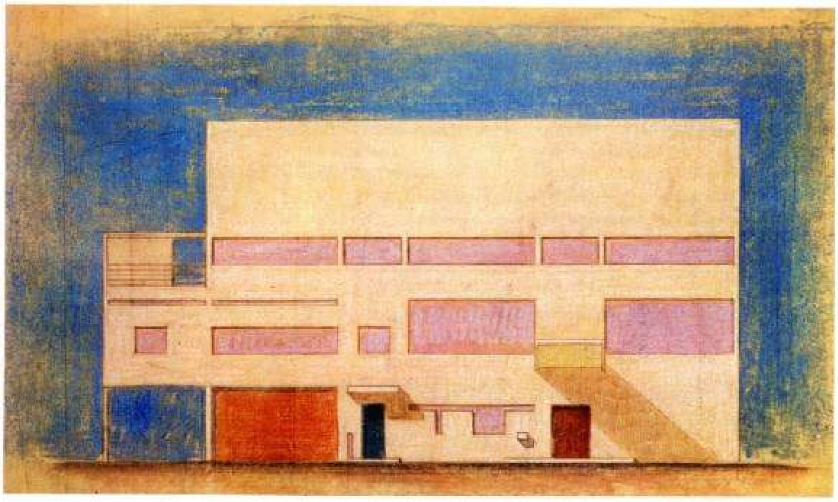

Figure 1. 24. Le Corbusier. Study for the Stein House, Garches 1927. Mixed technique with coloured crayons. Fondation Le Corbusier, Paris.

1.4 The illusion of reality

Photography has been an invention that has exerted a great influence on all artistic expressions. In the nineteenth century, this new technique was still in an experimental phase and the attention of the photographer was focused on people more than on buildings and landscapes. It was during the last century that previously unthinkable performances/outcomes became possible in the field of representation. Photography became a useful tool to create new kinds of images that met the tastes of the public. Despite its wide use, its application in architecture remained initially quite marginal, a tool for photomontages to simulate the future building in its environment and for pictures in illustrated magazines. Some criticism about its reliability in representing reality that involves the complex interaction between maker and viewer were already risen by scholars and art critics and are items debated even today (Kenney, 2005). Thus, the traditional drawing was far from being considered outdated. A metaphor was found by C. Recht between a painter (or a drawer) and a photographer: '*The violinist must first produce the note, must seek it out, find it in an instant; the pianist strikes the key and the note rings out. The painter and the photographer both have an instrument at their disposal. Drawing and colouring, for the painter, correspond to the violinist's production of sound; the photographer, like the pianist, has the advantage of a mechanical device that is subject to restrictive laws, while the violinist is under no such restraint. No Paderewski will ever reap the fame, ever cast the almost fabulous spell, that Paganini did*' (quoted in Benjamin's essay of 1931) (Benjamin, 1979, p. 249).

1.4.1 Photography and drawing

Photography was not universally accepted by architects as a substitute for drawing, neither in the stage of exploration of existing buildings nor in the final phase of presenting their own works already done. Le Corbusier repeatedly opposed freehand sketches to photography. In 1960 he wrote: '*When someone travels and understands visual arts -architecture, painting, or sculpture- he uses his eyes and draws, so as to fix inwardly, in his own experience, what has seen. Once the impressions have been recorded by the pencil, they stay inside forever, they are* *registered, inscribed. The camera is a tool for idling; we give a mechanical device the task of seeing for us*' (Le Corbusier, 2008, p. 37, translation by the author). Sometimes his drawings were taken directly from photographs. '*This practice of drawing an image after it has already been fixed by the camera appears throughout Le Corbusier's work, recalling his no less enigmatic habit of sketching his own projects again and again, even long after they have been built. He redrew not only his own photographs but also those he encountered in newspapers, catalogues, postcards*' (Colomina, 1994, p. 93).

Frank Lloyd Wright was keen on photography, but he saw limits in that technique. When he decided to submit his early works to the European public, he prepared a publication that should become one of the most admired and influential of those years, the Wasmuth Portfolio edited in Berlin in 1911. Wright chose to show his prairie houses and utilitarian edifices already built mainly by means of drawings. These had been made by himself or by his skillful illustrators' team that included an outstanding drawer, Marion L. Mahony. In his essays Wright had already made known his disbelief about the camera. '*To have imitated the natural modeling and position of the subject photographically in order to give a realistic topography of features and form would have been little and have required but manual dexterity and a mechanic's eye…A picture should be more than an imitation of a real object'* (Brooks Pfeiffer, 1992, p. 43). *'Photographs do not adequately present these subjects. A building has a presence, as has a person, that defies the photographer*' (Brooks Pfeiffer, 1992, p. 92). The architectural historian H.A. Brooks claims that at least ten eye-level perspectives in the Wasmuth Portfolio (1910) were copied from photographs. He takes as an example the Tomek House comparing the drawing with an earlier photograph: '*The fidelity of the copy is extraordinary; it even embraces the setting. Each tree has been carefully traced, including the branches and the shaggy bark. The house is the same, line for line, even to the open bedroom window. The only additions are urns of flowers at either side of the porch, and a change in the direction that the shadows fall*' (Brooks, 1966) (Figg. 1.25 and 1.26).

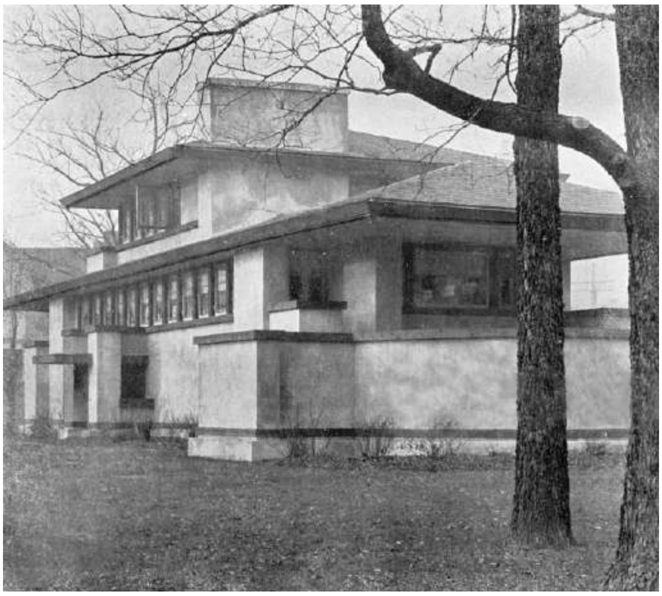

Figure 1.25. Frank Lloyd Wright, Tomek House, Riverside, Illinois. Photo made during winter 1907/08. F.L. Wright Foundation, Taliesin West, Scottsdale, Arizona.

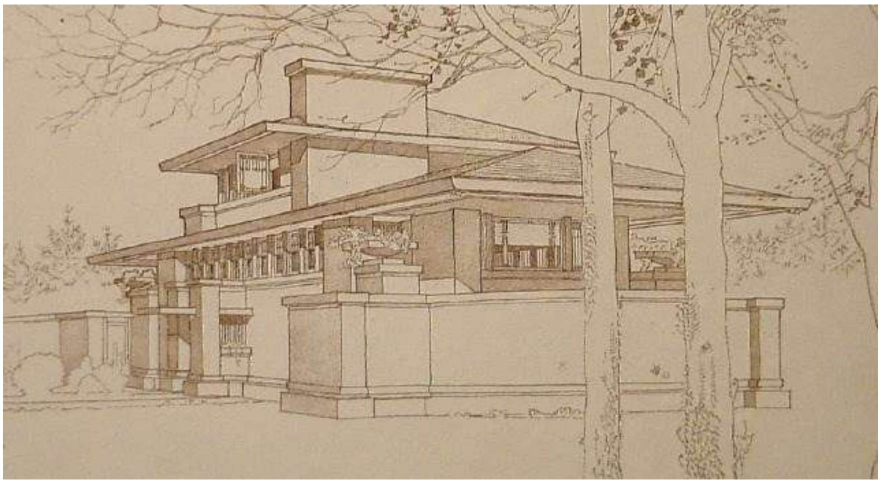

Figure 1.26. Frank Lloyd Wright, Tomek House. Wasmuth Portfolio, 1910. Watercolour and ink on art paper. F.L. Wright Foundation, Taliesin West, Scottsdale, Arizona.

The Larkin Building too, a newly built edifice intended for the offices of a company, was presented as a drawing in the refined Wright's style where the compact mass of the building- that had arisen some criticism- was lightened by the skillful use of lines and shadows (Figg.1.27 e 1.28).

Figure 1.27. Frank Lloyd Wright, Larkin Company Administration Building, Buffalo, New York. Photo made in 1903. F.L. Wright Foundation, Taliesin West, Scottsdale, Arizona.

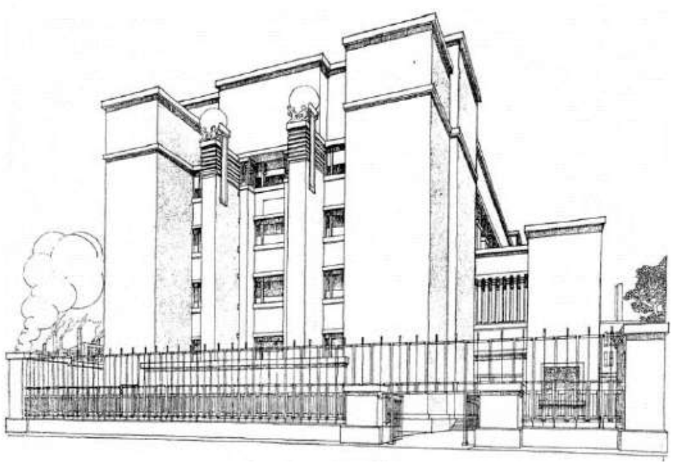

Figure 1.28. Frank Lloyd Wright, Larkin Company Administration Building. Wasmuth Portfolio, 1910. Watercolour and ink on art paper. F.L. Wright Foundation, Taliesin West, Scottsdale, Arizona.

If Le Corbusier and Wright had made a countercurrent choice, since the 30s the traditional perspective hand drawing seemed overshadowed by the new photographic representations. Photography was considered a powerful means of communication that could influence public opinion and promote architecture. It became evident for architects and illustrators that the camera was a true antagonist when it was about competing on the same ground, namely portraying an existing building. Cyril A. Farey, a British successful illustrator, pointed out: *'What remains then of architectural draughtsmanship if there is no longer any need for realistic drawings of existing buildings? This is a question easy to answer, for there is obviously one thing that a photograph cannot do, and that is portray a building which has not yet been erected*' (Farey and Edwards, 1949) (first edition 1931) (p. 12). The render in figure 1.29, made by Farey in the traditional British style, combines evident realism and meticulous accuracy. Farey only used watercolour, with the occasional white highlighting. His distinctive style is recognisable by the soft shadows and variations in tone and light on the building surfaces, by the pale blue sky and the wet roads reflecting the building (Stamp, 1982, p. 134).

If Farey showed realism in a traditional way, other illustrators made images like photographs. The picture of London traffic on a rainy day is vivid and realistic in this drawing by D. Muirhead Bone, where figures and vehicles passing down the streets are rendered using the same tones of the building (Stamp, 1982, p. 133). The intense mobility creates a visual counterpoint with the static massive building. It appears as the beholder is looking at the street from an upper floor facing the building. The overall effect, the viewpoint and the framing, can be compared to a black and white camera snapshot (Fig. 1.30). '*Modern architecture becomes 'modern' not simply by using glass, steel, or reinforced concrete, as it is usually understood, but precisely by engaging with the new mechanical equipment of the mass media*' (Colomina, 1994, p. 73).

Figure 1.29. Edwin L. Lutyens. No. 68 Pall Mall, London. 1928. Perspective in pencil and watercolour signed by Cyril A. Farey. Drawings Collection of the R.I.B.A., London.

Figure 1.30. Adams, Holden & Pearson. No.55 Broadway, Westminster, London. c. 1927. Perspective in pencil and watercolour by David Muirhead Bone. Drawings Collection of the R.I.B.A., London.

Photographies were partially used by architects during the design process: photomontages could give an idea about future shapes and masses and help to perceive the impact of the proposed building in the surroundings with almost realistic effects. The image presented with the photomontage technique was not a representation made to deceive the onlooker by simulating a non-existing reality. It appeared to be just an attempt to help the client's imagination to envisage the future building in its context (Fig.1.31).

Figure 1.31. Ludwig Mies van der Rohe, Project Berlin, Friedrichstrasse 1928/29. Photomontage. Museum of Modern Art, New York.

During the 60s some groups of young architects, critical of consumer society and traditional architecture, publicised their unconventional and provocative ideas by means of drawings and photomontages. One of the most influential was the London-based Archigram, which successfully spread innovative proposals in order to create a new concept of architecture, more flexible and dynamic. Their magazine drew people's attention to imaginary projects where ephemeral cities could change form and place thanks to technological devices. These projects were explained and illustrated, by means of hundreds of architectural drawings where new graphic tools, like in contemporary Pop Art, were experimented. Archigram images brightly coloured and mixed with photocollages were appreciated by the general public and had an immediate and long lasting impact also in architectural thinking (Cook and Archigram (Group), 1999) (Fig. 1.32).

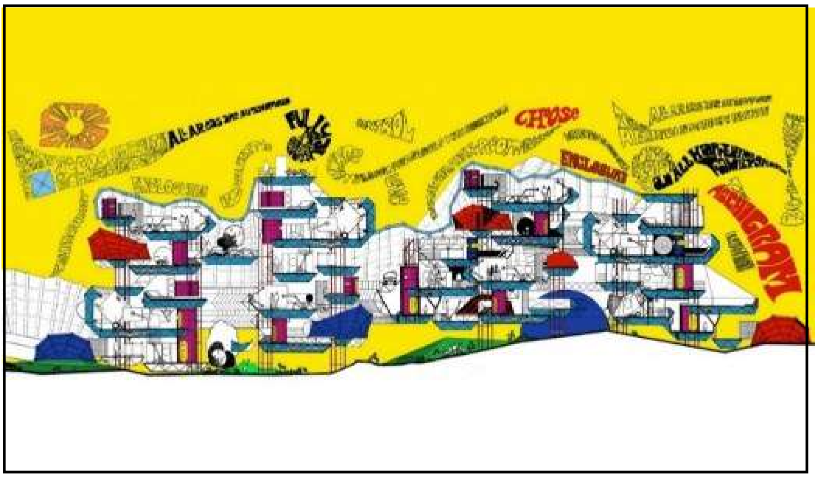

Figure 1.32. Archigram. 'Control and Choice' Project-Housing Study, Section. 1967. Ink on tracing paper, cut and pasted print, transparent colour overlays. M+Museum, Hong Kong.

In the same years, the Florence-based Superstudio presented the 'Continuous Monument' as a utopic '*architectural model for total urbanisation*' that could be located across landscapes and cityscapes. Not a technological megastructure but instead an enigmatic orthogonal shape with a flat white surface whose faint transparency did not allow interior views. The project was presented in architectural magazines initially as a series of photomontages (Fig. 1.33) and shortly after was developed into a storyboard performed as a freehand comic strip (Lang and Menking, 2003; Stauffer, 2002). In Fig. 1.34 the sketch of the Monument made in pencil contains this caption "*One may cross deserts, cover canyons, link together alpine lakes, or else use geometrically hills and rivers with new horizons*". The two images have without doubt a different visual impact on the observer.

Figure 1.33. Superstudio. The Continuous Monument. Photomontage entitled 'Alpine lakes': cut-and-pasted printed paper, coloured pencil and oil stick on board. 1969. Museum of Modern Art, New York.

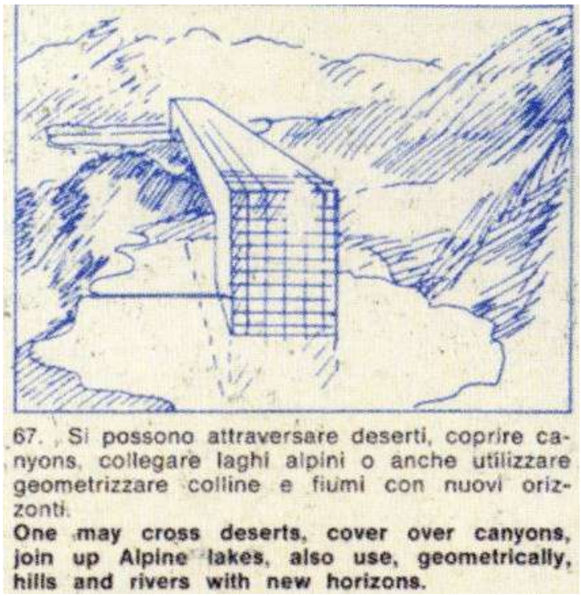

Figure 1.34. Superstudio. The Continuous Monument. Drawings for a storyboard. Blue pencil on paper,1969. 'Casabella', XXXV, 1971, n. 358.

1.4.2 A view on Wonderland: the digital photorealistic render

From the late-twentieth century, computer technology has taken over as a powerful means of communication and dissemination of images with an ever increasing efficiency and precision. Computer graphics and virtual images have radically transformed the traditional understanding of drawing, challenging the complex discourse on visual representation. In such a context the new techniques have been widely and successfully used by architects since they are sophisticated tools to make realistic three-dimensional renders. Furthermore, the digital visualisation process can extrapolate photographic-like images with extreme accuracy of details, materials, colours and lighting effects. At the same time animation of inside and outside spaces anticipates the daily life of the future.

Digital images are appreciated mostly by a wide audience who have no previous knowledge of technical drawings and are inclined to appreciate architectural works less than other visual arts. As W. Benjamin had already envisaged in 1935 essay on the age of mechanical reproduction, "*Distraction and concentration form polar opposites which may be stated as follows: a man who concentrates before a work of art is absorbed by it…in contrast, the distracted mass absorbs the work of art. This is most obvious with regard to buildings. Architecture has always represented the prototype of a work of art the reception of which is consummated by a collectivity in a state of distraction…The public is an examiner, but an absent-minded one*" (Benjamin, 1969, p. 18).

To catch the attention of this distracted public, photorealistic renders seem to be the best solution, mostly since they are perceived as similar to other visual images already assimilated through the mass media. In theories on visual communication formulated in the twentieth century, the concept of perception became more complex than before and a large number of variables were included. The relational character of perception and the role of the background are stressed. Perceptions are regarded both as a result of interaction between perceiver and perceived, and as consequence of past experience. Adaptation-level theory proves that the perceptual response may be represented as a function of the difference between some present stimulus process and an internal standard derived from the effects of previous stimulations: '*an individual's attitudes, values, ways of structuring his experiences, judgments of physical, aesthetic and symbolic objects, intellectual and emotional behavior, learning and interpersonal relations all represent modes of adaptation to environmental and organismic forces…Stimuli impinge upon organisms already adapted to what has gone before, and internal states depend upon previously existing internal conditions as well as external inciters to action'* (Helson and Murphy, 1964, p. 37). The adaptation level is a dynamic concept: it is the level of previous experience to which the single subject has adapted his behaviour. Today, the modern media of communication, mainly visual channels, affect the perceptual process in such a pervasive way that even the act of watching an image can't elude the influence of the cultural background. Television programs, movies, magazines, websites, commercial press create a world filled with images. The creation of realistic virtual spaces has shifted to the unfolding of 'nonplaces' beyond the real in the videogames simulation. In this age of digital mass communication, '*whereas a representation finds its original referent in the real, a simulation generates a new "real" without an original*' (Sturken and Cartwright, 2018, p. 209).

The likeness of a photorealistic render with an actual photograph, including detailed specific stereotypes of the daily life, makes the simulation hidden and create in the public extremely positive expectations, not matching with the future more trivial reality. '*The co-existence of both the realistic view and the fictional vision as a new simulated reality problematises the distinction between experiences of natural reality and experiences of artificial photo-reality. Rendering cuts through the naïve trust we have instilled in photographic images because our perceptual framework is confused by conflicting messages: 'This must be real!' and 'This cannot be real!''* (Bernath, 2007).

Jacob says that '*drawing packages and supersophisticated renderware, have narrowed the scope of architectural drawing even as they have exponentially increased its precision*'. The illustrative role of a digital realistic representation has often produced images as '*glossy visions of soon-to-be-built projects, usually blue-skied, lush-leafed, and populated by groups of groomed and grinning clip-art* *figures, where buildings appeared with a polished sheen*' (Jacob, 2017). The 3D renders, according to de la Fuente Suárez are ' *the product of standardized methods and are not intended for experiencing buildings, as they are created by using the representational styles, techniques and aesthetics of the moment*'. This kind of representation '*does not promote awareness of the building as a producer of experiences and, therefore, does not function as a tool or method of research on the design process*' (de la Fuente Suárez, 2016). D. Bernath points out a risk for western culture, already affecting some architectural companies in far-east countries: could this mechanism of rendering production escape the control of the design? '*This is where the rendering process is accentuated to a point of crisis in the design, where the image reinserts itself back to influence the outcome of the design process. The hypothetical projection of the rendering is hijacked and fed back into the loop of design prematurely; instead of saying 'it could be like this', the rendering dictates over the design to say 'it must be like this'…The effectiveness of rendering is potentially in competition with the effectiveness of the design at the moment of realisation*' (Bernath, 2007).

1.5 Creativity and Design

In the last two decades some proposals arose to find new methods of drawing especially in the initial phase of the creativity, i.e.the sketch, and in the final representation of the architectural object. Two different paths have been suggested to reach a compromise between the traditional handmade image and the increasing use of digital media. P. Cook seems to have chosen the 'hibridisation' of the drawing, made initially via computer, then retouched manually to render it more evocative and seductive (Cook, 2014). M. Frascari instead looked forward to new digital tools that allowed more flexibility and manipulation during the design process (Frascari, 2001). An adequate answer to this last speculation could be the digital drawing tablet, a comparatively recent device that imitates almost to perfection pen and paper, brush and canvas or other traditional implements.

1.5.1 Creative drawing in today's culture

The ubiquitous spreading of photorealistic rendering has caused different attempts to shift the boundaries of architectural representation to more creative contexts, working out other kinds of images less realistic but more expressive and evocative. Criticism about computer-generated imagery had arisen even previously in the visual arts field and novel research was undertaken in computer graphics called *non-photorealistic rendering*. These types of images were not judged by their likeness to photographs, instead they were appraised from their level to focus the viewer's attention (Gooch and Gooch, 2001). The meaning of architectural drawing, its link between an idea and its achievement has been widely debated since the 80s. '*The functional and rational sides of representation were increasingly reinforced by poetic and irrational characteristics. No longer is mere information offered to the attentive observer; the drawing presents itself to the imagination as material for play. The drawing is now to be understood as a kind of object for meditation, which transfers perception postures, sensibilities and ideas instead of "things"'* (Meisenheimer, 1987). P. Cook defines drawing as the motive force of architecture. '*Drawing -of every kind- is a motor that absorbs imagination and converts it into usable or transferable information or inspiration, thus self-consciousness is but another form of evaluation'* (Cook, 2014, p. 211).

The initial antithesis between screen and paper seems to have recently established a balance between a predetermined pseudo-photo-realism and alternative forms of drawings that allow flexibility, imagination, even provocation. Architects and artists have tested and redefined mixed images that simultaneously inform and create pictorial effects. They are at once digital and manual drawings, part paintings and part assemblage, and offer to the onlooker visual evidence of multilayered levels of interpretation. This does not exclude the choice of using exclusively the digital or analog medium in an original way that goes beyond a mere realistic representation. '*To have the whole thing plotted out beforehand and entirely predictable and therefore just a graphic exercise – this is infinitely boring. A drawing should be an investigative device, a voyage of discovery, a series of glances into the future*' (Cook, 2013). '*There will always be the need for the speed, the wit, and those bursts of* *inconsistency in hand drawing that the procedures of the digital process tend to find indigestible*' (Cook, 2014, p. 218). Some architects feel the need to free themselves from definite trends in illustration, experiencing various graphic representations to express their architectural thinking. The drawings selected are a small set of different forms of visualisation, which range significantly in both the illustrative intents and the graphic techniques (Figg. 1.35, 1.36, 1.37, 1.38, 1.39).

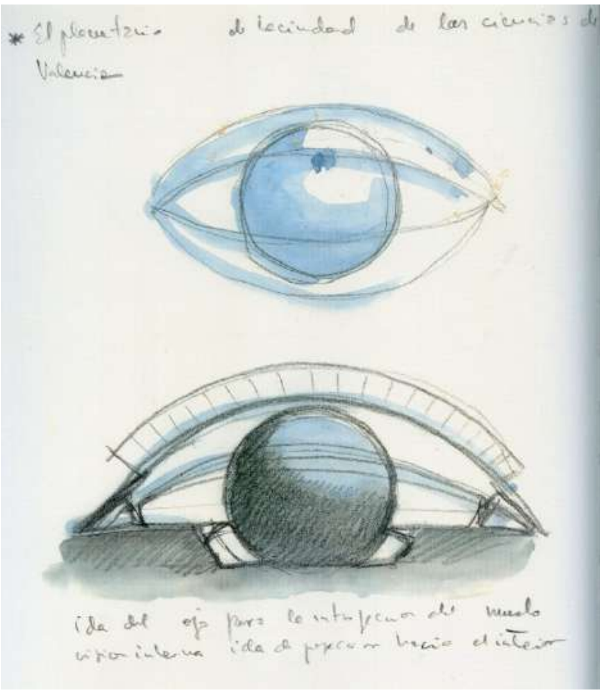

Figure 1.35. Santiago Calatrava, City of Arts and Sciences, Planetarium, Valencia. c.1990. Pencil and watercolour on paper.

The themes of movement and natural forms are a persistent inspiration in Calatrava's works of art and architecture: the opening and closing of a flower, the flight of a bird, the movement of the sun, the gestures of the human body. Architecture can generate a dynamic equilibrium: '*Unlike repetitive elements such as columns, canopies, concrete domes etc., mobile elements have a heterogeneous formal character; in other words, each follows a design born of the particular situation… their distribution nevertheless creates a functional unity* ' (Tzonis and

Lefaivre, 2001, p.60). Calatrava, as a Renaissance artist, believes in anthropomorphism as a generator of forms. '*I consider the body to be the most beautiful and functional of all natural objects; in its proportion and construction there is something essential that relates to the souls of both architecture and engineering*' (Carrillo de Albornoz and Calatrava, 2018, p. 17). '*Could there be any easier and more precise way to create rhythm and beauty in an artwork than to follow the secret "music" dictated by the body?*' (Carrillo de Albornoz and Calatrava, 2018, p. 41). The expressive gesture of the hand and the movement of the perceptive eye are favoured artistic motifs. In Figure 1.35 Calatrava imagines an eye with a moveable eyelid structure as the starting point for his design; to use his words: '*the idea of the eye for the introspection of the world – internal vision idea of perception from within*' (Tzonis and Lefaivre, 2001, p. 234). '*The image of the eye is used as the generating element for the building while water, as a reflecting film, becomes an additional architectural device enabling duplication of the image. A complete element is thus created, based on two symmetrical halves: one real, and the other virtual or reflected*' (Tzonis and Lefaivre, 2001, p. 190).

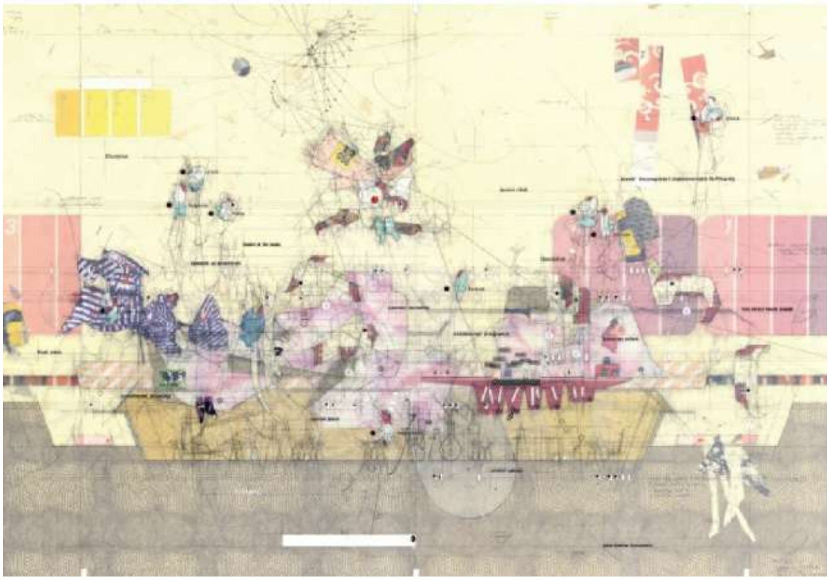

Figure 1.36. Perry Kulper. Competition design for Central California History Museum, c. 2010. Graphite, collage and varied media on plastic film.

Kulper' creative hand drawings are both informative and imaginative. Pencil lines used in differential weights, delicate tones, a myriad of overlapping, but never invasive, detail in varied media attract and intrigue the observer. As the author maintains: '*Rather than… limiting the role of the drawing to a metrical description of a project, ideas are augmented through an emerging visual field of study that is discovered in the act of constructing a drawing. Design in this sense is fluid, weaving heterogeneous ideas, discussing one disciplinary set of questions in relation to another, and through the rehearsing of design skills in the drawings themselves, fusing visualization and thinking as a relational and synthetic practice…Doing this through lines and composited layers rather than through the logics of construction allows my work to incorporate both necessary and unexpected cultural and natural considerations*' (Kulper, 2013)

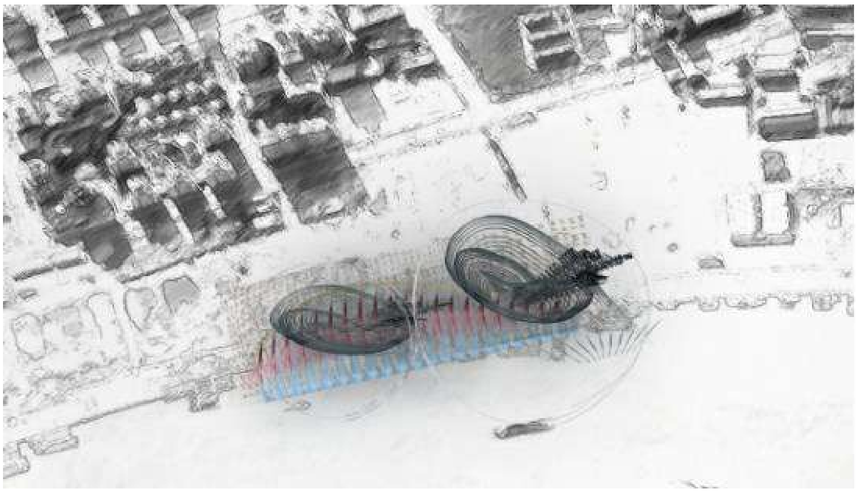

Figure 1.37. Kenny Kinugasa-Tsui. Cultural waterfront scheme in the Wang Pu Jian area, Shanghai. 2011. Colour pencil strokes on watercolour paper, scanner, Photoshop, 3ds Max.

This sketch by Kinugasa-Tsui (Fig. 1.37) shows the volumetric composition of the waterfront structures interacting with the existing site. As the author explains, after a first colour pencil drawing, 3D Studio Max ® makes easy to explore spatial composition. '*The original analogue hand stroke qualities would intrinsically intertwine throughout with the digital 3-D modelling process, thus allowing the benefits of preserving a certain "looseness" and "softness" in the sketches, while simultaneously capable to explore complexities of multiplications, fragmentation, and other geometric manipulations offered by the computer software. The camera in the 3D software allows each stroke to be spatially explored in "mathematically correct" perspectives*' (Cook, 2014, p. 208).

Figure 1.38. Peter Cook. Vegetated City 2012. Detail. Ink, watercolour and coloured pencil.

Since Archigram until today, Cook never ceased to investigate new forms of imagery, to carry on unpredictable performances of *'speculation-by-drawing'*. '*There are the constant questions of imagination versus hard information, the familiar versus the rhetorical, plus the underlying issue of clarity and accuracy. For it can be that to prosaically represent "only what can be there" is to miss the point. If we "observe" on the one hand and "create on the other", there is surely the potential for alchemy*' (Cook, 2013). This hand drawing has been produced, as his author asserts, for conceptual design purposes, for stimulating a thought process. '*It* *follows the Romantic idea of a city on several peninsulas and islands' with inclusion of many kinds of vegetation. 'The palette of the pencil crayon heavily wrought into the paper gives the whole thing a slightly "toy-box" air*' (Cook, 2014, p. 236).

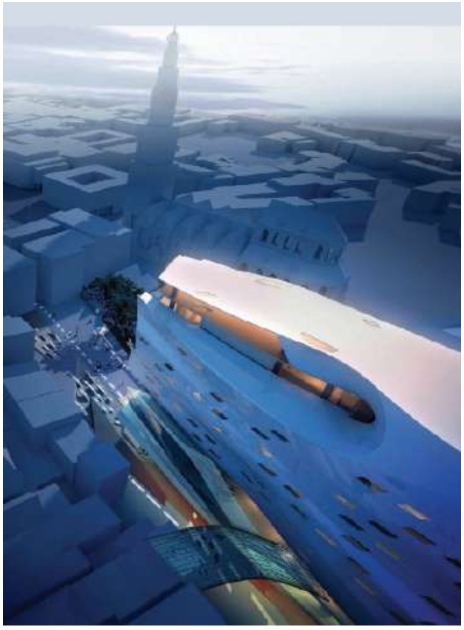

Figure 1.39. Zaha Hadid Architects. Groningen Forum. 2014. CAD Render.

According to Zaha Hadid, her drawings are not the building, but 'about' the building. They are not illustrations of a final product, rather they are tools to explore ideas, a way to see whether something is right or wrong. Her use of colour was often misunderstood. The colours in the paintings were not the colours of the building, but a study of light on its surface depending on time, transparency, quality of materials, sense of movement and energy (Futagawa, 1995). In this render (Fig. 1.39), the pictorial effects strike the observer who is involved in the aerial view of the proposed building. Colour and movement play a crucial role. The blue-grey tone of the background context and the lights from inside convey attention to the building that appears as a plane just landed at night. Zaha Hadid Architects mainly use V-Ray for Maya, Rhino and 3ds Max.

1.5.2 The freehand digital drawing

The usual medium to sketch and draw has always been some kind of paper on which several types of drawing implements like pen or pencil are used. According to the pigment, the trace may be more or less easily erasable, so corrections can be made, but always within limits and with some effort and time wasting. Besides, to draw in colours or to obtain some effects, an array of pencils must be available and anyway they have to be tended by appropriate sharpening and care. Using pen and ink is even more troublesome, mainly because afterthoughts or errors are not permitted, given the difficulty in erasing. All these implements have been employed for many decades, though with improvements that made their use easier (the modern wooden graphite pencil has mainly been perfected in the course of the XIX century). In design, be it architectural or industrial, the introduction of CAD solved most of the tedious operations of the pencil and paper drawing. The input of cartesian coordinates either by keyboard or mouse would trace perfect lines that, if needed, could be deleted in a moment without leaving a clue of their previous presence. That solution, though useful for the technical side of a project, would not permit the freedom of the hand drawing. Hand drawing is analogic, pertaining to the real world of the infinitely divisible, on the contrary CAD pertains to the digital world, the world of integer numbers. However, the computer offers attractive flexibility and facilities. So how to combine the freedom of the hand drawing on paper with the commodities provided by computers? The exponentially growing progress of solid state electronics provided the answer. The movements of the pencil can be traduced into very tiny bits, still integers, but so tiny that the resulting track memorized on storage medium cannot be distinguished by human eye from the continuous flow of a real sign on paper. The paper was substituted by a surface sensitive (the tablet) to the position of a dedicated stylus, which had to be used as a pencil. Next to the digital conversion of the movement, the most critical item was the stylus, which should provide the same grip and freedom as a pencil. This was not to be in the first implements, because they had to be connected with leads or be battery powered. Things are now changed, and the styluses are now wireless and with no batteries, taking power from an electromagnetic pulsating field generated by the tablet.

Consequently their dimension is the same as a pencil, they are sensitive to thousands of pressure levels, so the trace can be more or less marked; they are also sensitive to tilt and rotation with the trace size and shape changing accordingly. Finally, one of the latest and most important improvements has been the combination of a screen with the sensitive surface of the tablet. So the tip of the stylus seems to actually interact with the surface, with a perfect alignment, just like tracing on paper. Sophisticated raster software is also available as free open source applications, allowing imitation of all sorts of pencils, pens, brushes and sprays of any dimension and colour. Multiple layers can be created or deleted to test superimposition effects. But the most important feature of all remains the strong similitude to draw with pencil or pen, conferring the same haptic sensation to the hand, which moves freely and effectively while drawing on this new contrivance. Just as the drawing implements had evolved through the centuries, so the digital tablets should be regarded as a novel drawing medium that can blend the perception and creativity of the freehand drawing on paper with the commodities offered by the computer. We may well assert that freehand digital drawing is not an 'oxymoron', but a new method still maintaining the creativity necessary to any design. As freehand drawing is now possible on digital tablets with a likenes unthinkable just a decade ago, some of the fears rightly asserted against computerized drawing are going to be dismissed. Just few years ago.it was remarked that: '*The computer creates a distance between the maker and the object, whereas drawing by hand…puts the designer in skin-contact with the object… In drawing by hand and pencil/pen, the hand follows the outlines, shapes and patterns of the object, whereas when drawing by mouse and computer, the hand usually selects the lines from a given set of symbols that have no analogical – or, consequently, haptic or emotional – relation to the object of drawing. Whereas the hand drawing is a mimetic moulding of lines, shades and tones, the computer drawing is a mediated construction*' (Pallasmaa, 2009, p. 97). And also: '*The physical grasping develops drawing tactics through both haptic interactions based on the manipulation of tools and the tacit learning due to the peripheral senses becoming aware of the rules embodied in the movements of the tools themselves … Architects live between two realms: a physical and a virtual environment … At* *present, we are torn between these parallel, but disjoined spaces. The invention of new architectural tools can lead to novel demonstrations of architecture. They have to be prosperous not prescriptive instruments, but manifestations of architectural thinking*' (Frascari, 2011, p. 136). Quite surprisingly, these new implements merging the freehand drawing with the world of computer facilities have not been taken on by designers as much as it should be expected from the tremendous potentialities it offers. A few examples of the results that can be obtained by exploiting the current available technology as hardware and software are given in figures 1.40, 1.41, 1.42. 1.43.

One of the reasons why tablets are not in current use by designers may possibly be found in the still enduring belief that CAD drawing may solve most quickly all problems of design, especially in the architectural world. There is little doubt that if the designer is faced with a limited range of solutions , all of them proposed by the available software, the choice would be much easier than finding a solution by insight. The first process is an easy one, driven by the outside, whilst the second, the insight, would require an inner effort of fantasy, creativity, courage. A tendency to obtain results with the minimum effort and as fast as possible has no doubt much facilitated the use of CAD even since the first steps of designs and has possibly fascinated and biased generations of students . However, the warnings issued towards the indiscriminate use of CAD are now starting to be listened by more and more professionals and there are signs that freehand drawing will return to be employed in many steps of the design process. So, it is hoped that a balance between the use of CAD and freehand drawing will soon be found in the professional and academic world. The new tablets will then offer an ideal solution to foster creativity in design on one side, and to meet time deadlines on the other, thus matching the needs of professional design studios.

Figure 1.40. G. Leandri. The Studio Museum in Harlem, New York. Adjaye Associates, London. 2018. Drawn with Wacom tablet Cintiq 27QHD TDK and Photoshop.

Figure 1.41. G. Leandri. 130 William, Northeast view. Detail. New York, Adjaye Associates, London. 2017. Drawn with Wacom tablet Cintiq 27QHD TDK and Photoshop.

Figure 1.42. G. Leandri. 130 William, Entrance View. New York, Adjaye Associates. London. 2017. Drawn with Wacom tablet Cintiq 27QHD TDK and Photoshop.

Figure 1.43. G. Leandri. 130 William, Marine Drive. Accra. Adjaye Associates. London. 2018. Drawn with Wacom tablet Cintiq 27QHD TDK and Photoshop.

PART 2

QUESTIONNAIRE ON ARCHITECTURAL IMAGERY

Part 2 Questionnaire on architectural imagery

2.1 Background

2.1.1 Visualisation-The eye of the observer

This part of the research is meant to investigate the effect of architectural imagery on the observer, who is supposed to receive the image-maker's message and formulate meanings based on his/her perceptions. This visual interaction, occasionally supported by written words, is now taken for granted, albeit it has undergone criticism like any other form of imagery, regarded with suspicion as a misleading means of communication. This mistrust, or even refusal, has ancient roots. In western and middle-eastern religions only the word had a sacred significance. Also in Greek culture antagonism towards images appeared among the philosophers' teachings. In the *Republic* Plato disregarded painters as magicians and imitators. Images, easy sources of leisure, could draw people away from sacred writings or cultural discourses. Furthermore, there was the steadfast wariness about images as fake representations of nature: they pretended to be something different from reality and were regarded as imitations of appearance instead of truth (Stephens, 1998, p. 60). Images found a supporter in the Catholic Church. In 599 Pope Gregory First wrote: '*We do no harm in wishing to show the invisible by means of the visible*'. In the thirteenth century, Thomas Aquinas defended the usefulness of images: they are easily accessible to illiterate people who might learn from depictions as if from a book. Besides, images can arise emotions that are more effectively elicited by things seen than by things heard (Stephens, 1998, p. 61).

From the Renaissance onwards 'explaining by drawings' was considered a reliable tool of communication by scientists who found images the necessary complement to their writings, for instance, in botany, anatomy, geography, astronomy. Also architects used technical drawing in the design process. This kind of image was never questioned since it was in several cases more effective and comprehensive than words. Perspectival drawings instead were sometimes an issue of speculations and criticism. They were considered ambiguous. If we can learn to read words, usually we are not trained to read images and construct their meaning. In this case we have to refer to mental models built by experience and '*we make* *sense by comparing the reality before us with the mental abstractions we store in memory…The human brain's ability to quickly process new information is based on prior knowledge stored in mental categories*' (Reaves, 2005). The realistic images generated by digital technology have been considered the ideal solution to create effectual representations and facilitate the observer's understanding.

In university courses students are taught to use CADs and virtual reality applications. They have learned to appreciate the speed, ease of use, precision and stunning special effects, but they are walking a path which may lead to addiction and impair fantasy (Guney, 2015). The representation of a project, a building or a townscape, needs realism but still has to convey the spirit of the designer and to this end, too detailed visualisations may not be agreeable (Farey and Edwards, 1949). This point of view has prompted some authors to avoid the excessive, cold realism of photographic renders in favour of a handmade artwork (Richards, 2013). As much as perception is the one's notion of reality formed through the biological channels of the body (Arnheim, 1998), so the drawing is a representation materialised through the work of the hands, the final product of an embodied experience (Pallasmaa, 2009). In modern design, digitally made 3D renderings of photographic quality are extremely popular and easy to make. Most authors praise such products even on grounds of creativity because various solutions can be simulated and tested in just a few moments (Ivarsson, 2010; Khan, 2018; Lawson, 1997). But the asserted 'creativity' only lies inside the application world created by developers; it is a limited creativity, an oxymoron in itself, against which several warnings have been issued (Bernath, 2007; Lawson, 1997). We are now in an age where handcrafted representation is often considered outdated and uselessly time-consuming, whilst virtual reality is easy to produce and perceived as authentic as a postcard (Jacob, 2017). Little thought is given to the fact that postcards and creativity do have not much to share. But postcards also have other drawbacks. Can they be considered a reliable language, can they convey the author's ideas? Perhaps not as well as manual drawings.

2.1.2 Simulation- The misled eye

Photography, after an initial enthusiasm for its being considered a mirror of the reality, was mistrusted as soon as it provided the possibility of the 'montage', that is a hundred years ago: pieces of pictures allowed to be pasted together to create new untrue, yet intriguing, images. The traditional notion of reality could thus be disassembled. Visual manipulation was then possible, but still required a time-consuming craftsmanship, technical skills and an artist's eye. Things changed since the introduction of computer graphics in the '80s of the last century. Since then, artificial pictures that can be perceived even more real than the actual objects are within the reach of anybody who could handle a computer. Digital tools can create a seducing reality that is taken for granted by onlookers.

Simulation, nowadays very popular, is a novel creation where everything is known and completely under control. It is '*an artificial environment that creates an artificial experience that is felt to be reality*' (Scheer, 2014, pag 31) Anything can be done but on condition that it stays within the constraints of the provided frame, be it software or hardware. There is no ambiguity, there is no incompleteness, there are no divergent ideas. The rules are set by the authors of the simulation application, so no user can develop ideas outside it.

The outstanding quality of nowadays photographic renders raise the issue of a professional ethical behaviour on account of the author, who should not provide ground for biased judgment by the observer, inducing false positive expectations. Most studies on public's perception of computer simulations investigated the perceived sense of reality, wellbeing and other qualities of the illustrated design, but the ethical issue of simulations seems to be rather unattended in the architectural field. Conversely, newspapers and magazines deal extensively with this matter. A survey made by Reaves (Reaves, 2005) assessed that newspaper editors were very critical of any kind of digital manipulations of photographies, whilst magazine editors were more tolerant about glamorous illustrations. A picture in a newspaper should be perceived as 'natural' and accordingly informative and educational. The magazine photo illustration must catch the imagination, it should be creative and pictorial, and some positive bias could be tolerated or even encouraged. The ethical dilemma arises when readers or onlookers do not understand that a photography's intent is just to create illusions (Wheeler and Gleason, 1995). '*New technology often outpaces our understanding of its effects…The digital scalpel has changed the ethical query "What's wrong with this picture" to a more cynical question: "What's wrong with this perfect picture*?"' (Reaves, 2005, p. 455). Photorealistic renders fall in the category of the magazine glamour pictures, so it is to the author's ethical principles to keep the simulation within the limits of something agreeable to the eye without trespassing into distorted reality.

2.1.3 Communication-The mind of the observer

In the implementation of a project, representation is an integral part of it, to the benefit of the designer and the public. If the graphic expression can be an anticipation of a building that doesn't exist yet, it plays an even more important key role in the design of a city project, where the visual image alone has to deal with manifold features on different perceptual levels. The purely abstract act of creation becomes a project in the mind and hands of the designer and should be conveyed in the right way in order to make an abstract thought real to the beholders. The image of the project becomes a project of the image where invention and analysis of the existing must establish a dialogue between the designer and the final user. Therefore it is essential to define what is the best means of communication.

The word 'communication' comes from the Latin 'comunicare' , which stands for sharing, making common. Hence the term has been defined as the process of understanding and sharing meanings (Pearson and Nelson, 2000). Meanings can be conveyed by gestures, by words and by images. Due to the complex nature of language, occasionally the best and almost only method to experience it is through an image. So, the most important step in communication between designer and public is to convert the ideas, either still unmaterial or already reified, into drawings. The choice of communicating meanings through a visual channel provides a number of potential advantages. The most important of them is perhaps the capacity of the onlooker to perceive at a single glance features belonging to the whole picture and that could not be conveyed by written or spoken words. In this visual communication the creativity of the image-maker is entrusted to the message with the aim to be perceived by the beholder, who interprets it with a new and independent act of creativity (Dake, 2005). According to the channel, or modality, chosen to convey the architectural message, such advantages can be fully or just partially exploited. The investigation reported in this section aims at assessing whether there is any evidence that a visual message transmitted through a freehand drawing may convey the author's intent differently than a digital photographic render.

2.1.4 Previous investigations on photographic rendering

There have been a number of reports on the reception by the observers of photographic renders or architectural hand drawn images. It appears that the main focus of investigations has been whether such images could be perceived as realistic (Bates-Brkljac, 2012). These have been fostered by the trend of exasperated photorealism that now pervades computer generated images, so that it may be hard to differentiate them from a photograph of something real (Nastasi, 2016). Since the first introduction of CAD, its undeniable advantages have led to the current situation where no architect can present a project which has not been CAD processed. Realism through digital images seems to be the ultimate goal of the presentation process. The old traditional hand drawn images, though still in some use, seem to be forgotten, particularly in the educational field. Working preferences for students are strongly biased towards an entirely computerised world (Şenyapili and Basa, 2006).

Dichotomy between digital and hand drawn images has been the object of some studies inquiring whether digital images are perceived as a more comprehensible and effective tool of communication than the handmade representations (Bates-Brkljac, 2011, 2009; Iñarra Abad et al., 2013). The results were partially dependent on the background of the audience, mainly whether they were architects or other professionals. Computer generated images were generally perceived as more accurate and realistic than traditional illustrations, a characteristic mainly appraised by the non architects (Bates-Brkljac, 2009). All in all, architects prefer artistic images and pay attention to attributes as innovation and functionality, whereas non-architects prefer photoidealistic images and pay attention to the wellbeing feeling conveyed by the digital image (Bates-Brkljac, 2011). One more important issue is represented by meeting the consumer's preferences and needs, as already occurs in the field of industrial design (Iñarra Abad et al., 2013; Llinares Millan and Iñarra Abad, 2014).

2.2 Materials and methods

2.2.1 The questionnaire

A simple questionnaire was constructed and named 'Architectural Drawing 3.0'. It was an online web questionnaire created on Typeform, an interactive platform which allows to combine images and text. It was run on Instagram and LinkedIn throughout a duration of two months, during which random people were targeted, with no limitation in number. It was conceived for a wide range of different users that could represent the heterogeneous public usually reached by architectural imagery. The questionnaire had been designed according to recent overviews (Mittal & Mittal, 2011); the questions were of the following typologies:

1- Text questions which assessed the user background, interests or attitudes towards drawing tools and renders;

2- Multimedia test which provided textual and multimedia contents (images) with a true or false type of answer;

3- Multimedia test with a single preference type of answer, for which the general impression of the user was the parameter we were seeking.

The two multimedia tests were conventional one-stem multiple-choice type with correct answer scored 1 and wrong answer scored 0 (Ng & Chan, 2009). The position of correct answer in each question was randomised by the Typeform platform. The whole questionnaire was divided into six sections.

2.2.2 First section on status information

The first section just asked questions #1) age, #2) gender and #3) occupation. All questions were of the close ended type, so the answers could be precisely cathegorised. Age groups were a) 19 and under, b) 20-29 c) 30-39, d) 40-49, e) 50-59, f) 60 and over; gender a) male, b) female; occupation a) architect, b) student, c) civil/construction engineer, d) architectural assistant, e) architectural illustrator, f) 3D artist, g) academic (in the architectural field), h) interior/product designer, i) deeloper, j) real estate agent, k) other.

2.2.3 Second section on 'Communication'

The second section, containing questions #4 (Fig. 2.5), #5 (Fig. 2.7), #6 (Fig. 2.9). #7 (Fig. 2.11) was named 'Communication', meaning that it was aimed at assessing how much the visual message (vignette) would communicate to the observer its meaning as novelty and originality of a newly designed project, to be recognized among others already existent. The comparison was between hand drawn illustrations versus photorealistic renders: which of the two would best communicate to the onlooker. Question #4 showed a vignette with a hand drawn image which illustrated a new project among other already existing city buildings. Four vignettes with already marked different buildings were offered as possible solutions. Only one marked the correct new project. Question #5 showed a similar hand drawn project, but with only two vignettes as a choice. Question #6 was analogous to #4 but the illustrations were photorealistic renders. Question #7 was analogous to #5 but now photorealistic renders showed the project.

2.2.4 Third section on 'Recognisability'

The goal was to assess how much the 'sign' of the author of a project could be recognised in hand drawn illustrations compared to photorealistic renders. The test takers were first shown 3 hand drawn images authored by as many famous architectural companies (Fig.2.15, right column) , and 3 photorealistic renders from the same (Fig. 2.15. left column), in order to familiarise themselves with each company style. In question #8 a set of 3 new hand drawn images by the same companies was shown (Fig. 2.16), unlabelled: the test takers had to pick up the correct combination of authorship just recognizing the style of the illustrations among 6 possibilities. Question #9 was analogous to #8, but this time the images were photorealistic renders (Fig. 2.19).

2.2.5 Fourth section on 'Engagement'

These two questions were just about personal preference between hand drawn or photographic render representation of interior design. Question #10 showed two similar living room projects, one as a hand drawn illustration and another as photorealistic render (Fig. 2.22). The test taker had to choose which one preferred. Question #11 was analogous, but showed a bedroom project (Fig. 2.23).

2.2.6 Fifth section on preferences in the use of images by architects

This section aimed at collecting data about professional use of images according to preferences of architects, and their desiderata about freehand digital drawing.

2.2.7 Sixth section on contacts and comments

This was mainly aimed at collecting comments on architectural imagery in general and suggestions for future questionnaires.

2.2.8 Data handling and statistical analysis

The web platform provided detailed data on a spreadsheet and some preliminary descriptive statistics and proportions with correct answers per each group of test takers. Differences in the proportions of right and wrong answers were tested by using the chi-squared ($\chi 2$) test. Fishers exact test was used if any of the cells had expected counts less than 5. All tests were conducted with $\alpha=0.05$ (5% level) and a null hypothesis of no difference between the two groups (reject null hypothesis/accept evidence of a difference if $p<0.05$ i.e. chance of wrongly saying there is no difference (false negative) was less than 5%).

2.3 Results

2.3.1 Responders

There were 154 full responders who completed the questionnaire. Of these, 77% were in the age range of 20-39 and 9% 19 or under (Fig. 2.1). So 86% could be defined young adults; 58% were males and 42% females (Fig. 2.2). Occupations are summarized in Fig. 2.3: architects represented 28%, students in the architectural field were 21%, civil or construction engineer 6%, architectural assistant 4%, architectural illustrator 3%, 3D artist 2%, academic 2%, interior designer 2%, developer 1%. The 'other' category scored 26%. So we decided to group all 'professionals' altogether, scoring a total of 74% of test takers, to be compared to the 'others' group (Fig. 2.4).

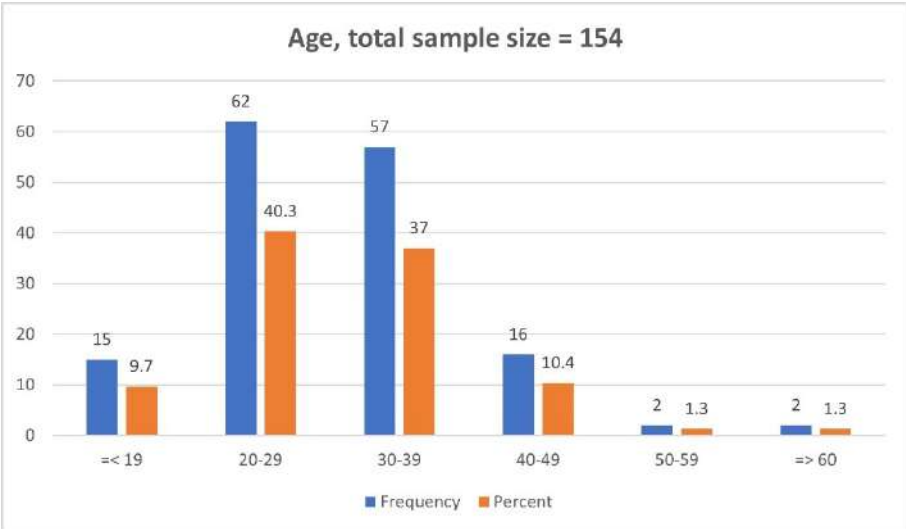

Figure 2.1. Question #1: age. Distribution of age of participants. The 20-39 range was the most represented. Graph by the author.

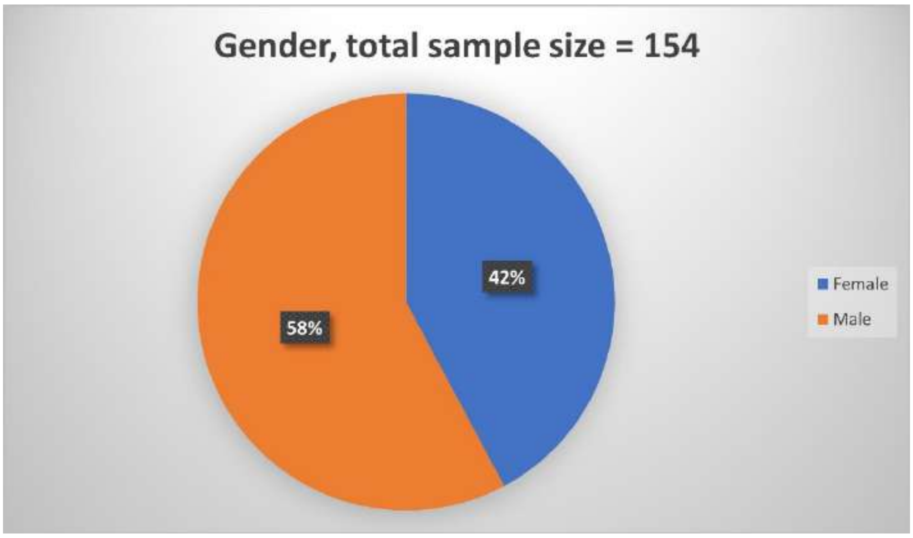

Figure 2.2. Question #2: gender of participants. Graph by the author.

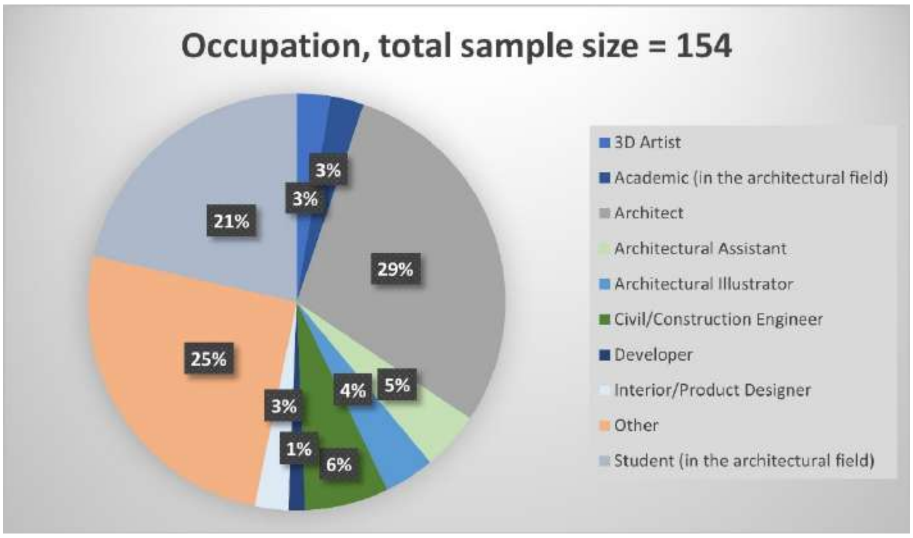

Figure 2.3. Question #3: occupation. All groups. Graph by the author.

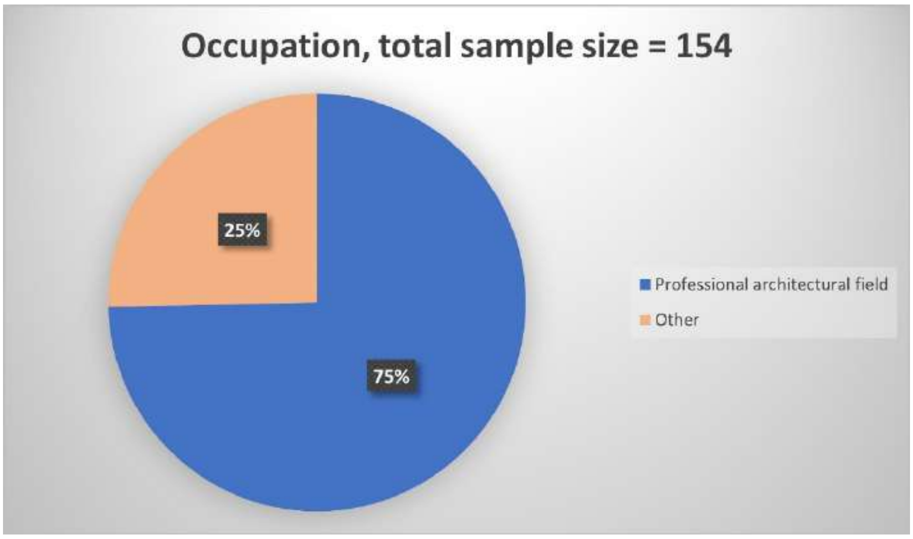

Figure 2.4. Question #3: occupation. Clustered in two groups. Graph by the author.

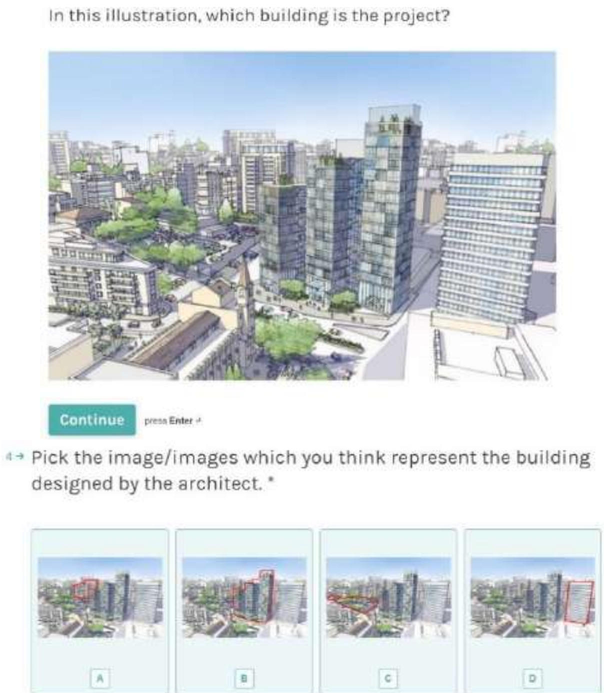

Figure 2.5. Question #4. 'In this illustration, which building is the project? Example of hand drawn image. Bankmed, Lebanon, John Robertson Architects. Image source: Archdaily.

2.3.2 Communication section: Questions #4, #5, #6, #7

Responses to Question #4 (locate a hand drawn project image in urban environment, 4 choices) (Fig.2.5) yielded 89.6% of correct answers by ‘professionals’ and 87.2% by ‘others’ (graph on Fig. 2.6). There was no significant difference between the two groups. A similar result turned out for question #5, with another hand drawn vignette (Fig.2.7), where correct answers were 93% in the case of ‘professionals’ and 82% for ‘others’ (graph on Fig. 2.8) . No significant difference between groups was detected.

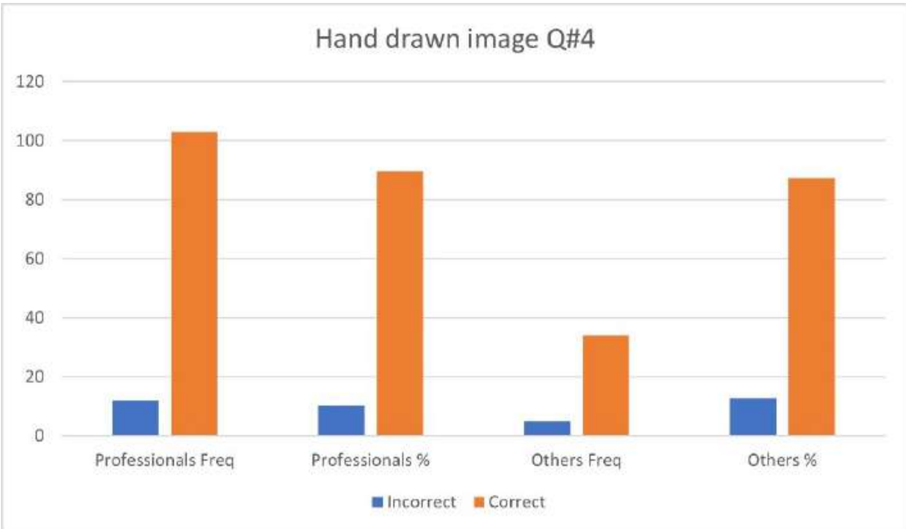

Figure 2.6. Question #4. Graph of correct and wrong answers to hand drawn image A. In both groups there is a very significant difference between correct and incorrect answers, and there is no difference between groups. Graph by the author.

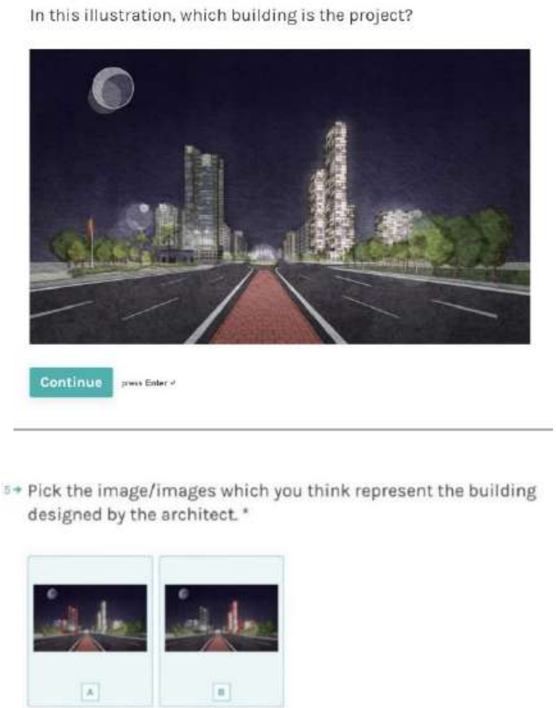

Figure 2.7. Question 5#. ‘In this illustration, which building is the project?’. Example of hand drawn image. Torre Laminar, Spain, Gallardo Llopis Arquitectos. Image source: Gaia Leandri.

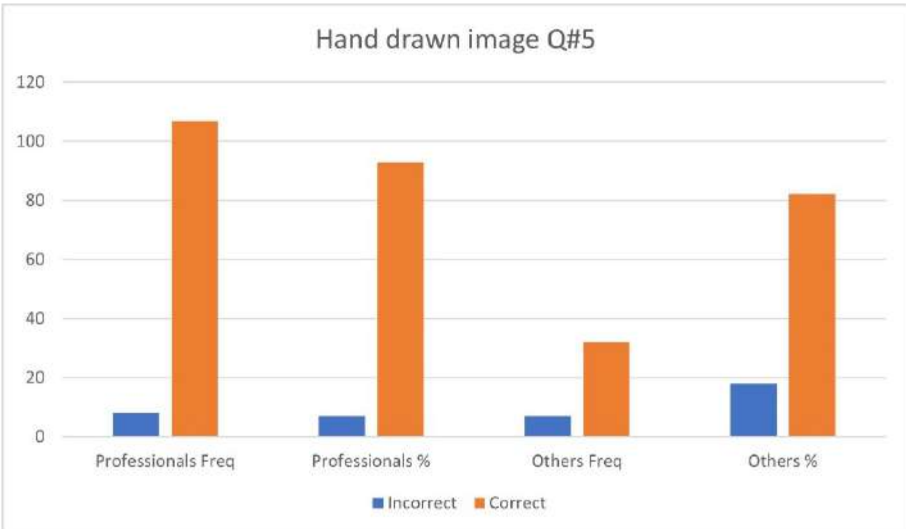

Figure 2.8. Question #5. Graph of correct and wrong answers to hand drawn image B. In both groups there is a very significant difference between correct and incorrect answers, and there is no difference between groups. Graph by the author.

Questions #6 and #7 (Fig. 2.9 and Fig. 2.12) concerned photorealistic renders, again there was no significant difference between ‘professionals’ and ‘others’ in each of the two questions: professionals were 23.5% correct in question #6 and 32% in question #7, while the ‘others’ proportions for correct answers were 12.8% (question #6) and 47% (question #7) (graphs on Fig. 2.10 and Fig. 2.13) . When the scores of the same group in recognising the project were compared between hand drawn images (questions #4 and #6) (graph on Fig 2.11). and photorealistic renders (questions #5 and #7) (graph on Fig. 2.14) , it came out a difference of 66.10% for ‘professionals’ and 74.40% for ‘others’ , with a very high significance level ($p<0.0001$) in both cases.

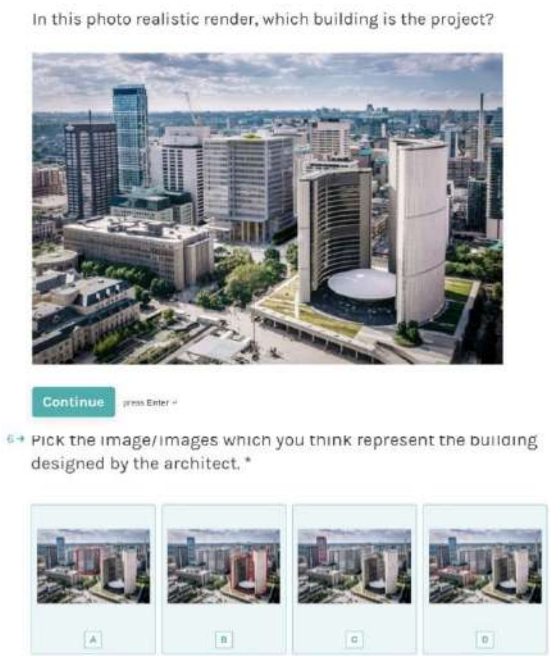

Figure. 2.9. Question #6. ‘In this illustration, which building is the project?’. Example of photorealistic rendering. Ontario Court of Justice, Canada, Renzo Piano. Image source: RPBW.com

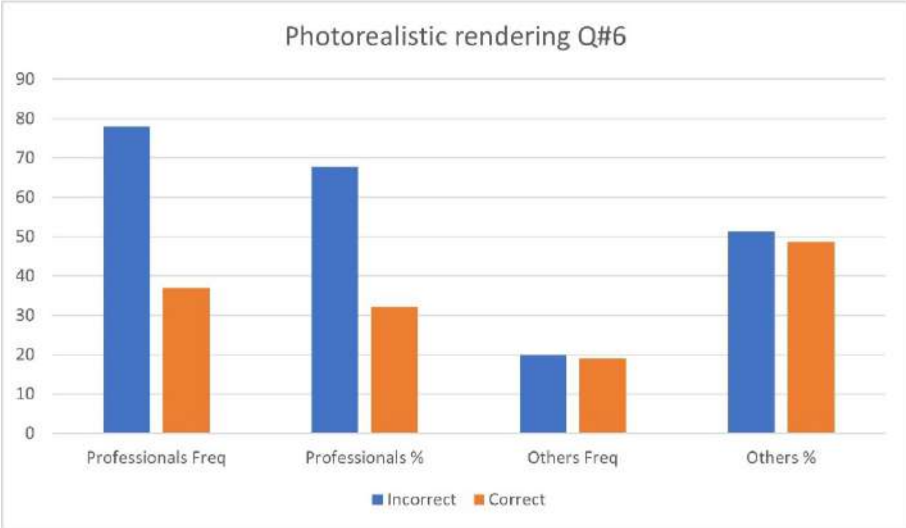

Figure 2.10. Question #6. Graph of correct and wrong answers to photorealistic rendered image. In both groups there is a very significant difference between correct and incorrect answers, and there is no difference between groups. Graph by the author.

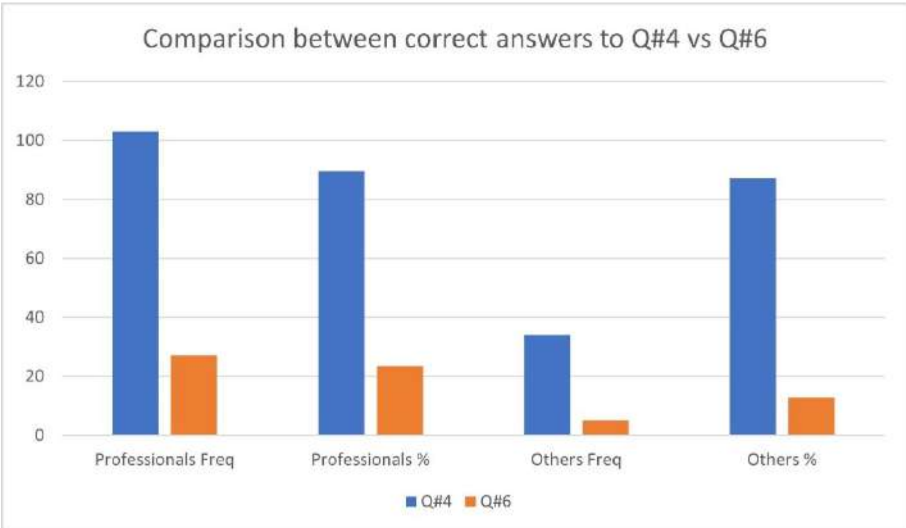

Figure 2.11. The score of correct answers to Q#4 (hand drawn image) was significantly higher than to Q#6 (render) for both groups. Graph by the author.

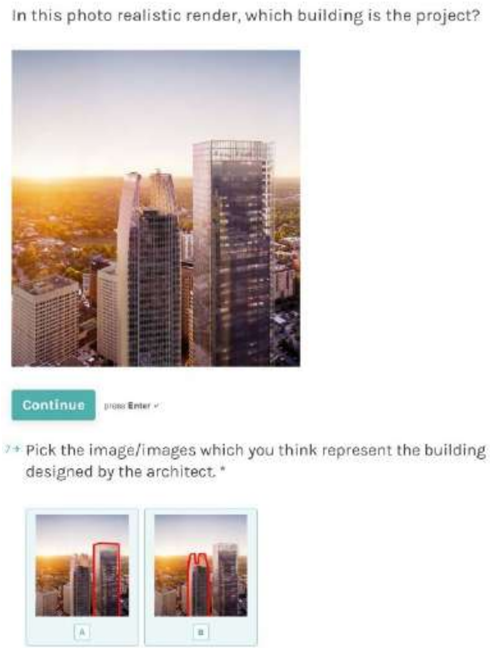

Figure. 2.12. Question 7#. ‘In this illustration, which building is the project?’. Example of photorealistic rendering. LVMH Tower, USA, Christian de Portzamparc. Image source: Christian de Portzamparc.

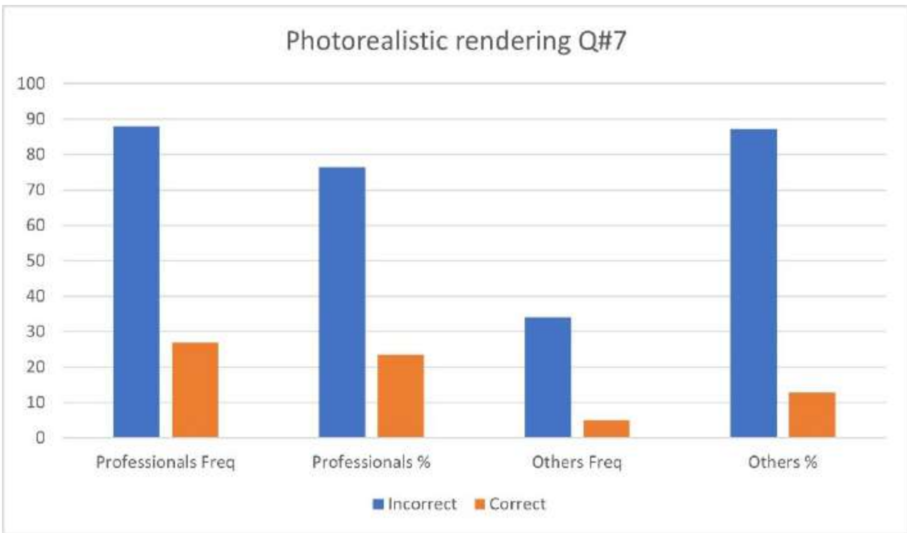

Figure 2.13. Question #7. Graph of correct and wrong answers to a photorealistic render. In both groups there is a very significant difference between correct and incorrect answers, and there is no difference between groups. Graph by the author.

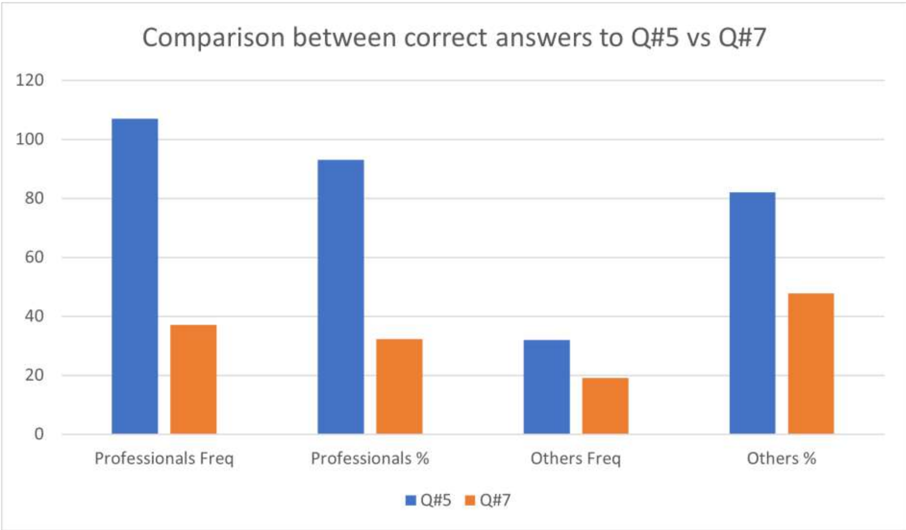

Figure 2.14. The score of correct answers to Q#5 (hand drawn image) was significantly higher than to Q#7 (render) for both groups. Graph by the author.

2.3.3 Recognisability section: Questions #8 and #9

The images were hand drawn and the test takers, after having familiarised with each company's style (Fig. 2.15), had to spot the answer with the correct labelling combination among 6 possible choices. The 3 hand drawn styles (Fig. 2.16) were correctly recognised by 70.4% of 'professionals' and 56.4% of 'others'(graph in Fig. 2.17) . The difference between the two groups was not significant. For question #9, the same procedure as question #8 was applied, but the images were photorealistic renders (Fig. 2.18). The 'professionals' scored 20.9% of correct answers, whilst the 'others' scored 23.1% (graph in Fig. 2.19). No significant difference between groups was demonstrated. Comparing the same group responding to the two questions (graph in Fig. 2.20), it came out that the 'professionals' showed a 49.50% score difference between the correct answers to question #8 and question #9, which was highly significant ($p<0.0001$). The 'others' also showed a significant difference of 23.1% ($p=0.0028$) between the two questions. So, both 'professionals' and 'others' scored more correctly in the case of hand drawn images than photorealistic renders.

Figure 2.15. Examples of images from 3 renowned international studios in hand drawn and computer generated photorealistic styles. These were shown for the test takers to familiarize with each studio's signature in both styles. Whittle School, USA, Renzo Piano. Image source: RPBW.co; Krause Gateway Center, USA, Renzo Piano; Image source: RPBW.com; Haknook Headquarters, Korea, Foster + Partners. Image source: Fosterandpartners.com; Mission Towers, USA, Foster + Partners. Image source: Fosterandpartners.com; Botanic Garden, Russia, Nikken Seskkei. Image source: Nikken.co.jp; Suzhou Hyundai Media plaza, Nikken Seskkei. Image source: Nikken.co.jp

Figure 2.16. Question #8, hand drawn images: 'using the previous set of images as reference, assign each illustration to the correct architect'. Only one correct combination should be chosen on the left hand table. Undefined, Nikken Sekkei, Imagine source: ASAI; Swiss Re House, UK, Foster + Partners. Image source: Pinterest; Whitney Museum, Renzo Piano. Image source: RPBW.com.

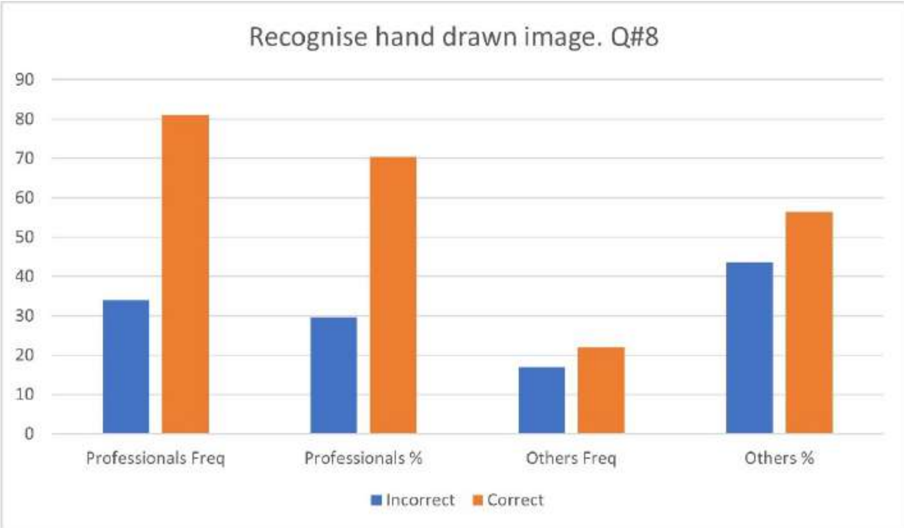

Figure 2.17. Graph of correct and wrong answers to question #8. In both groups the correct answers were significantly more than the incorrect ones. Graph by the author.

Fig. 2.18. Question #9, photographic renders: 'using the previous set of images as reference, assign each illustration to the correct architect'. Only one correct combination should be chosen on the left hand table. 555 Howard st., USA, Renzo Piano. Image source: RPBW.com; One Za'abeel, Dubai, Nikken Seskkei. Image source: Nikken.co.jp; South Quay Plaza, UK, Foster + Partners. Image source: Fosterandpartners.com

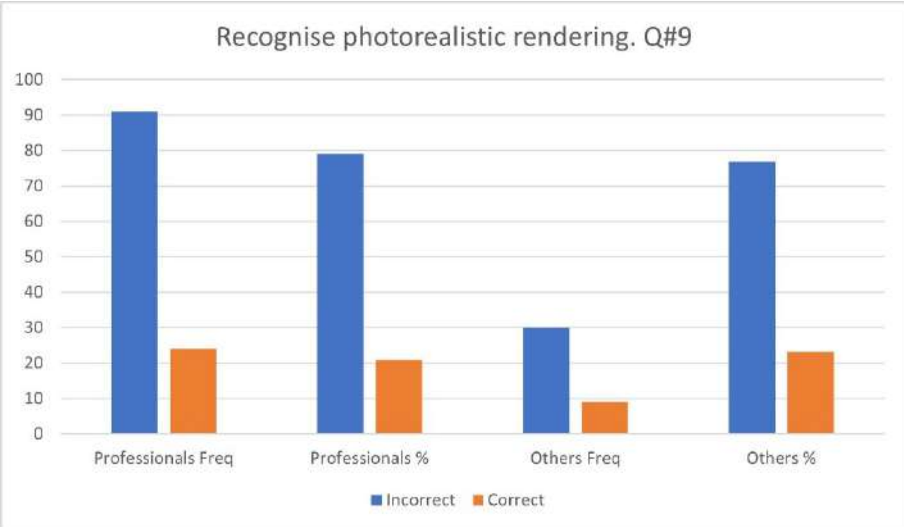

Figure 2.19. Graph of correct and wrong answers to question #9. Both groups scored significantly more incorrect than correct answers. There were no significant scoring differences between groups. Graph by the author.

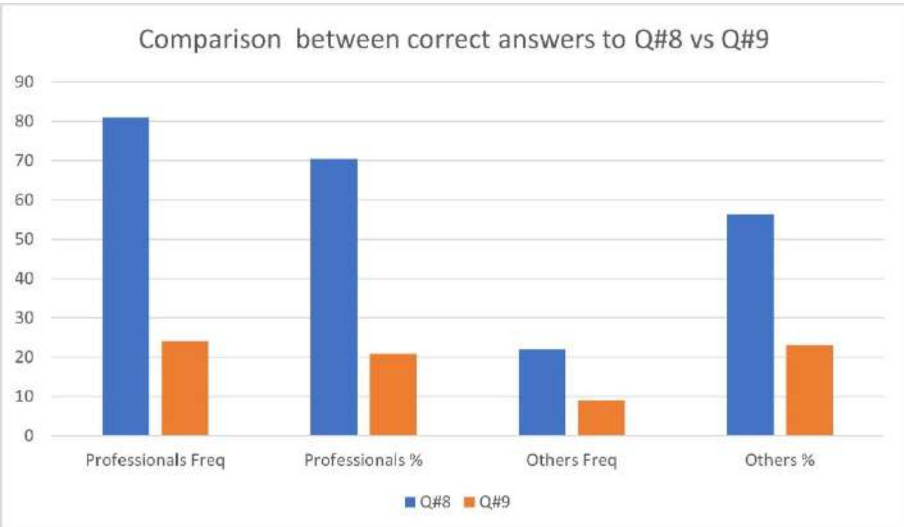

Figure 2.20. Comparison of performances from the same group to answer Q#8 and Q#9. The score of correct answers to Q#8 (hand drawn image) was significantly higher than to Q#9 (render) for both groups. Graph by the author.

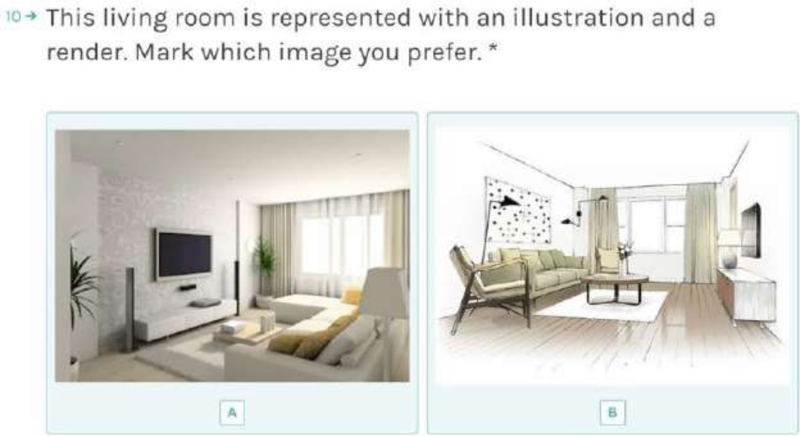

Figure 2.21 Question #10. In the first test on interior visualisation preference the subjects were asked whether they preferred a manual drawing or a CAD of a sitting room. The majority of professionals and others preferred CAD. Living room render: Wnetrzarium Properties; living room illustration: Street Easy Porperties, 3 Sheridan Sq.

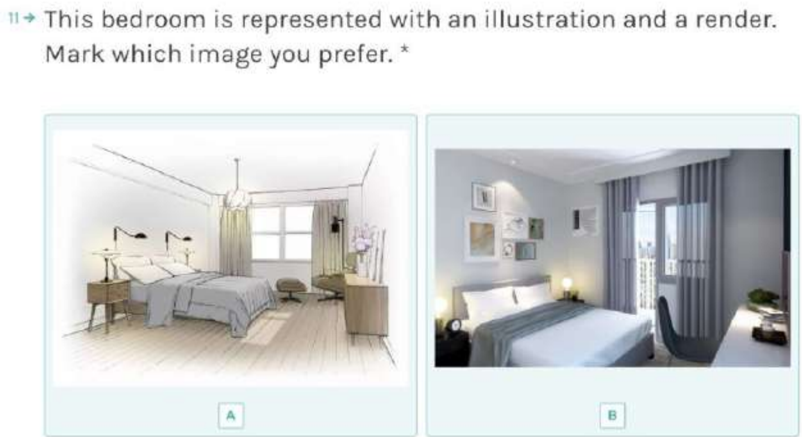

Figure 2.22. Question #11. In the first test on interior visualisation preference the subjects were asked whether they preferred a manual drawing or a CAD of a bedroom. The majority of professionals and others preferred CAD. Bedroom render: Megawrold Properties, Vion Tower; Bedroom illustration: Street Easy Porperties, 3 Sheridan Sq.

2.3.4 Engagement section

Questions in this section simply asked the observer for a personal preference between hand drawn illustration (Fig. 2.21) and photorealistic render (Fig. 2.22). The two options were presented in a different order for each participant, randomly organised by the Typeform platform. The perceptive 'engagement' was sought, with an answer presumably based upon the general impression and instinctive reaction by the onlooker. No statistics were performed to compare these results as the choice was strictly based not on performance but on personal taste, and could depend on the quality of image. Two images, one hand drawn and one a photorealistic render of two very similar living rooms and two bedrooms were presented. The 'professionals' group expressed a slight preference for the hand drawn living room (56%) against the photorealistic render (44%), but showed a reversed preference for the photorealistic bedroom (56%) against the hand drawn version (44%). The 'others' group expressed an almost perfectly even opinion, with 51% preference on the handrawn living room against the photorealistic render (49%), with identical proportion as to the bedroom. These results could be approximated to a 50/50 preference for both groups and for both representations.

2.4 Discussion

2.4.1 The test takers

The participants to the questionnaire responded to publicisation on some of the Web channels; their recruitment could of course be biased by the chosen channels, but it is deemed that they represented an audience generally interested in architecture and images. The 'other' group can be assimilated to the general public, without specific education on architecture or image crafting and processing; they were expected to respond more instinctively to the tests, without looking for technical assessments. The 'professionals', many of them architects, would look at the images from a more educated point of view, and, in theory, spotting better than the 'others' the correct answers to the proposed questions. We shall see that, eventually, the educated 'professionals' and the more naïve 'others' behaved very similarly.

2.4.2 The tests

The two main tests on communication and recognisability were addressed at assessing the ability of images to convey the correct message. All professionals and students in the architectural field do not only design buildings, they also need to sell their projects to clients, juries, public commissioners. The importance of images is paramount to such an end. When the observer looks at an image portraying more than one building, for example a bird's eye view or simply a view of the neighbourhood contextualising the proposed design, he/she may experience difficulty in spotting the project in a photorealistic render. In some cases the aim of the image may be how the still non-existent building will perfectly blend with the surroundings, but at the same time, such type of imagery limits the very scope of the architectural representation, which is to tackle the reaction of the observer to the project, to introduce critical concepts, to communicate the architect's emotions to the customer (Maller, 1991). Recognisability is obviously linked with the style in the design and presentation of the project. It is the 'sign' of the maker. One day, the author was at her desk, when her boss came in and asked: 'I need you to create a new style for the Company. Like Renzo Piano drawings, you know. Something recognisable'. Her thought went straight to the thin lines and the blue/yellow washed colours that are Piano's visual signature. As in every other industry, architecture is nothing less than a product behind which there is the name of the designer. Whether the object comes to life or remains unbuilt, whether it gets published on a magazine or presented at a competition, it is important for the architect, the 'seller' of the idea, to leave a personal trademark.

2.4.3 The answers

It may be surprising to find that architects and the general public had very similar reactions to the images presented. In both cases, the hand drawn images conveyed more correctly the information meant to be transmitted to the onlooker; a sure token of the greater efficacy by the hand drawn images to express the ideas and personality of the author. The photorealistic render, though needed in some circumstances in order to provide detailed information about the future results, may not have such important qualities. It is remarkable that whereas the objective qualities of communication and recognisability were assessed as belonging more to hand drawn images than to photorealistic renders, the subjective opinion on aesthetics a propos of the living and bedroom was a perfectly balanced response by ‘professionals’ and ‘others’. The dichotomy between the ‘objective’ and the ‘subjective’ sets suggests that the perception mechanisms of a pleasurable image are disjointed from the meaning that the image should convey. Both factors, on one side the personal feeling elicited by the image and arising inside the observer, and on the other the ‘sign’ and ‘communication’ of the architect (a more objective quality of the image) should be given attention

Summing up, in the handcrafted figure the new building was identified definitely better than in the photographic render. The message that the building had something special that characterised it from the others was clear in the hand drawn figure but much less clear in the render. Why was that? The hand drawn figure did not have peculiar features that could suggest which building was the new one; nevertheless it could be spotted in the majority of cases. Of course the experiment will have to be repeated several times with different styles of drawing and rendering, but this first attempt is a strong suggestion that there are differences that the conscious eye may not catch, but the unconscious might.

2.4.4 The possible underlying brain mechanisms

Of the classic Aristotelian five senses, the test takers only used vision to select their answers. So it is the neuroscience of vision that has to be investigated to get some reasonable clue as to the possible mechanisms underlying their choices. The visual cortex is situated at the back of the brain, in the occipital lobe (Fig. 2.23). Approximately at the centre of this lobe is the primary visual area, where the nervous afferents from the retina, after one intermediate relay, connect for the first time with cortical neurons. The latter are spatially arranged in a faithful map of the retina, called ‘retinotopy’. This part of the visual system is devoted to analyse some physical constituents of the image, called ‘visual primitives’ (contrast, line orientation, brightness, colour, movement and depth) (Gilbert, 2013), which are essential to recognise objects.

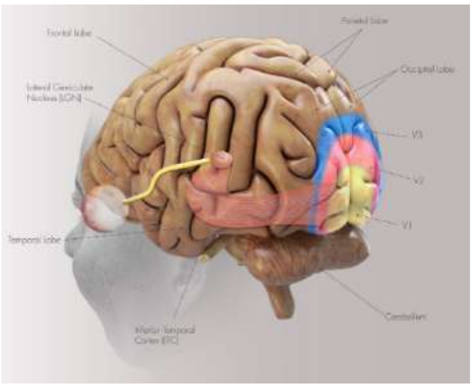

Figure 2.23. The visual pathway and cortex. The primary visual cortex (V1), where the retina is represented as a retinotopy is shaded in yellow. The other colours mark cortical areas (V2 and V3) where further visual processing takes place, with recognition of objects and faces. From https://www.ophthalmologytraining.com/core-principles/ocular-anatomy/visual-pathway/visual-cortex

. It is at this stage that most of the image characteristics aimed at social communication play their role. For example, definite angles of line orientation are better identified by cortical neurons. Drawing lines at such angles may catch the eye of the drawer, even unconsciously, who will use them more often than other lines. The observer's eye will also be caught by the same lines, and the object will stand up from the background, with little apparent reason. There are several of such hidden hallmarks that a handmade drawing might include unknowingly to drawer and beholder, but that will make the end product more communicative. Other cortical areas receive visual information for further analysis and comprehension, for example recognition of faces and complex objects. It is hypothesized that such more subtle analysis is based upon details of the image that are interpreted at a further level of cortical processing (Ullman et al., 2002). This could be another feature that easily escapes the conscious acts of drawing and observation, but that nevertheless plays an important role in the visual communication. It is easy to imagine that the introduction by the author of visual elements fitting the observer's visual perception may best be performed by a human hand, which could behave as an instinctive independent crafter, i.e. the ‘thinking hand’ of Pallasmaa (Pallasmaa, 2009), rather than by a computer which automatically creates a simulation. A summary of this first set of brain mechanisms is illustrated in Fig. 2.24.

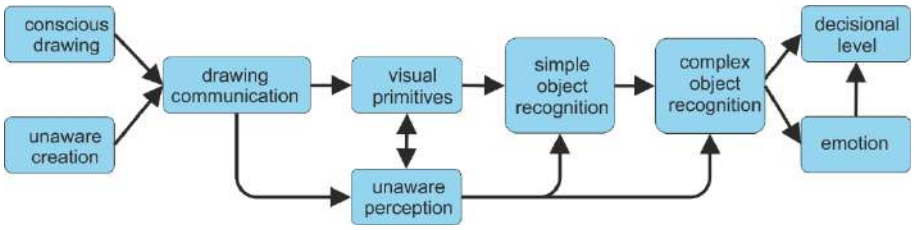

Figure 2.24. Processing of the visual information taking to decisional level. Flowchart by the author.

Another reason about the better performances by ‘professionals’ and ‘others’ when visualising manual drawings may reside in the amount of the visual ‘noise’ (Fig. 2.25). In communication theory, the object of communication, or the ‘signal’ should stand out as much as possible from the background. If there are elements other than the ‘signal’ present in the visual message, they are called ‘noise’: something unwanted, that disturbs the perception of the signal because creates an ‘interference’ changing the meaning of the message (McLean, 2005). It is easy to imagine that in the handmade image the author has to choose which features to draw from his/her design, thus filtering out the unnecessary details (the ‘noise’) and conveying to the visual message just the essentials, or the ‘signal’. Conversely, such noise filtering quality is denied to a photographic quality render, where all details are digitally reproduced with the same accuracy as the signal.

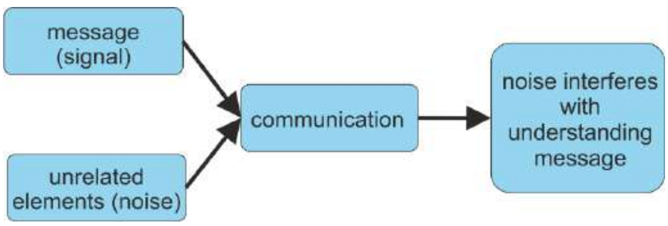

Figure 2.25. In communication unrelated elements (noise) are transmitted alongside the correct message (signal). When communication is received noise interferes with the message and impairs its understanding. Flowchart by the author.

Finally, the human hand may insert into its visual creation some properties peculiar of the whole image, unknown to the mechanistic process performed by the computer (Fig. 2.26). Properties of the whole have been theorised and studied by the Gestalt psychology most of all in the analysis of the images (Arnheim, 1974). The single components of an image do not possess properties that can be found in the perceived whole. Our brain, according to Gestaltists, processes visual perceptions by grouping constituents following preset principles, like, for example, proximity, similarity, continuation, closure, closeness and insularity (Wagemans et al., 2012). Some graphical specimens are shown in the figures 2.27, 2.28, 2.29. Such properties of the whole, or holistic properties, are thought to have a perceptual dominance attracting the observer's attention even without conscious perception (Wagemans et al., 2012). Although the basics of such theories were borne in an era by the dawn of experimental neurophysiology and could not be substantiated by scientific evidence, it is now recognised that the brain structure is provided with functional features underlying those principles. So called 'Gestalt' neurons have been found, for example, in the temporal lobe, responding to holistic characteristics of images while being insensitive to details (Spillmann and Ehrenstein, 1996). It is obvious that such holistic properties can be present in hand drawn images as the author is subject to the same Gestalt laws as the observer, but a machine made image will much more easily be devoid of them.

In summary, there are several functional factors based on identified brain mechanisms underlying visual perception that may explain why the hand drawn images have transmitted, at least in the presented tests, the author's message better than the digital photographic renders.

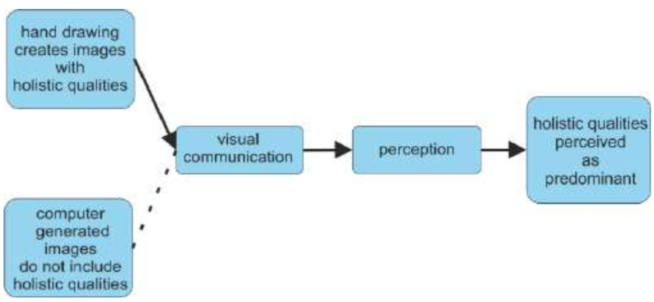

Figure 2.26. Holistic qualities are dominant in visual perception. Characteristics of single components may be disattended. Hand drawings are more likely to be permeated with holistic qualities. Flowchart by the author.

Figure 2.27 An example of the closure holistic quality. The eye only perceives spots, but the brain connects them integrating what the image lacks (closure) and recognises the shape of a dog. From https://www.usertesting.com/blog/gestalt-principles

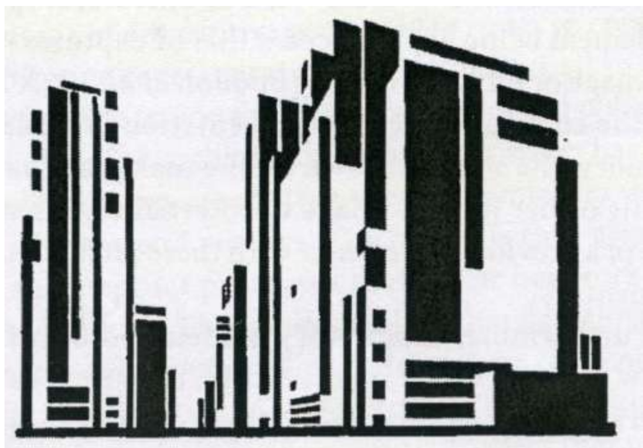

Figure 2.28 Several holistic properties: closure (perception of unrepresented boundaries), closeness (single entities are perceived as a whole) and insularity (completion of a unrepresented whole form) show up in this drawing by Yacov Chernikhov (1930), made of disjointed planes only.

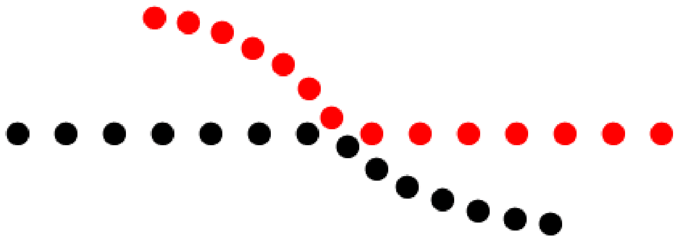

Figure 2.29. An example of the continuity principle: the eye follows patterns of straight or curved lines; broken lines are disattended. From https://www.usertesting.com/blog/gestalt-principles

2.4.5 Weaknesses of the tests

Most of the tests on architectural imagery usually submitted either to the lay public or architectural professionals are based upon preferences that are more or less quantified, often according to a Likert scale (Likert, 1932). The 'communication' and 'recognisability' tests used in this survey are instead based on the performance of the observers. This 'performance' strategy guarantees against subjective biases, but it has been much less experimented than the traditional paradigms. Some more research would be needed to assert its robustness, and, to this regard, this first attempt should be considered as a proof of concept to assess some observer's reactions so far little explored but nevertheless of fundamental importance.

Of course, the results of the tests can be influenced by the images chosen, so there might be a bias on the side of the test maker. Such drawback, anyway, is present in all tests based upon images and is independent from the test modality. In our case, extra care has been used in choosing images with similar contrast, brightness and, possibly style. No instrumental assessment of image qualities has been performed in our investigation; in future research this could better ensure equivalence between image sets.

Recruitment of test takers is another potential distorting factor of test results in general. In our case, recruitment had taken place through two main web forum platforms in sections dedicated to architects. It is possible that the small differences between the groups ‘professionals’ and ‘others’ were due to the ‘others’ being recruited through the same canals. Some more detailed assessment of the participant’s background will ascertain possible educational issues.

2-5 Conclusion

Handcrafted representation is thought to be aesthetically more pleasant and meaningful that photographic render (Richards, 2013), and the results of the reported web test support its superiority in communication too. Neuroscience provides some definite clues as to the involved mechanisms. Broadly speaking, these could be of three types. Firstly, the brain functions leading to a handmade drawing are the same that are used by the onlookers to watch and judge the drawing. Secondly, such mechanisms may not reach the conscious level neither on the part of the drawer nor on the part of the observer. Thirdly, the communicative property of the image is probably stronger if it happens at subconscious rather than at conscious level. Summing up, the properties of handcrafted images should be taken into due account both at educational and professional level, so that they can be used with proficiency alongside the photographic renders.

PART 3

THE CREATIVITY OF BRAIN AND HAND

Part 3 The Creativity of Brain and Hand

List of abbreviations

BP: Bereitschaftspotential
CT: Computerised Tomography
EEG: Electrocencephalogram or Electroencephalography
EMG: Electromyogram or Electromyography
ERP: Event Related Potential
fCTD: functional Transcranial Doppler
fMRI: functional Magnetic Resonancce Imaging
fNMR: functional Nuclear Magnetic Resonance
MEG: Magnetoencephalogram or Magnetoencephalography
MP: Motor Potential
MRI: Magnetic Resonance Imaging
MRP: Movemen Related Potential
NMR: Nuclear Magnetic Resonance
PET: Positron Emission Tomography
rCBF: regional Cerebral Blood Flow
RP: Readiness Potential
SEP: Somatosensory Evoked Potential
SQUID: Superconducting Quantum Interference Device

Declaration on published material as activity of the present doctorate.

The experiment 1 reported here has been performed in the first year of the doctorate and was preliminary to experiments 2 and 3. It has been the object of a publication in the Journal of the Neuroscience Methods (Leandri et al., 2021). Most of the text of the paragraphs describing and discussing experiment 1 is a transcript of the published paper, as are the related figures 3.21, 3.22, 3.23 and 3.24 and the table 3.1.

3 Brain and hands of the designer

Three experiments have been performed with the aim of exploring simple elements of brain activity preceding and following the act of drawing according to the saliency of the task.

3.1 Background

3.1.1 The hand creative view.

Drawing by hand has been the only accessible way that humans had to produce graphical images until the dawn of photography, and, more recently, computerized graphics. The enthusiastic acceptance of computer techniques has induced architects to produce images of their designs by computers rather than by holding a pencil. To understand how this abrupt and radical change in imagery could affect the very design process, it is mandatory to analyse the cognitive and biological processes behind image-making. Images are created to be seen, watched, understood, arise emotions. They communicate through the most phylogenetically ancient perception path, the sight. Sight conveys at a glance what words cannot do in a hundred written pages; it evokes feelings conscious and unconscious faster and more efficiently. These are the effects, wanted or sometimes unwanted, of the images; but how are they created, how are they loaded with pregnant meanings that, in the architectural field, are meant to transmit the creative spirit of the designer? Painting abstract or depictional images is a token of cognitive abilities already possessed by human beings in the Late Middle Paleolithic and is considered characteristic of modern human behaviour. The first testimonial of geometrical images goes back to approximately 70000 years ago in a cave in South Africa (Henshilwood et al., 2002). But it is in the Upper Old Stone Age (10-30000 years ago) that complex evoluted paintings by the Cro-Magnon people were made in caves of southern France (Fig. 3.1); there, the magic importance of the hand, which was felt to embody the drawer's spirit, is fully attested by the outlines of the same hands that (very likely) drew the pictures. Those are signatures, and, according to some plausible hypotheses, the signatures of women (Schmidt-Chevalier, 1981). They did not convey the authoress name, but possibly her sex and her character, as if we could stand before her and, looking at her hands, fully comprehend her insights.

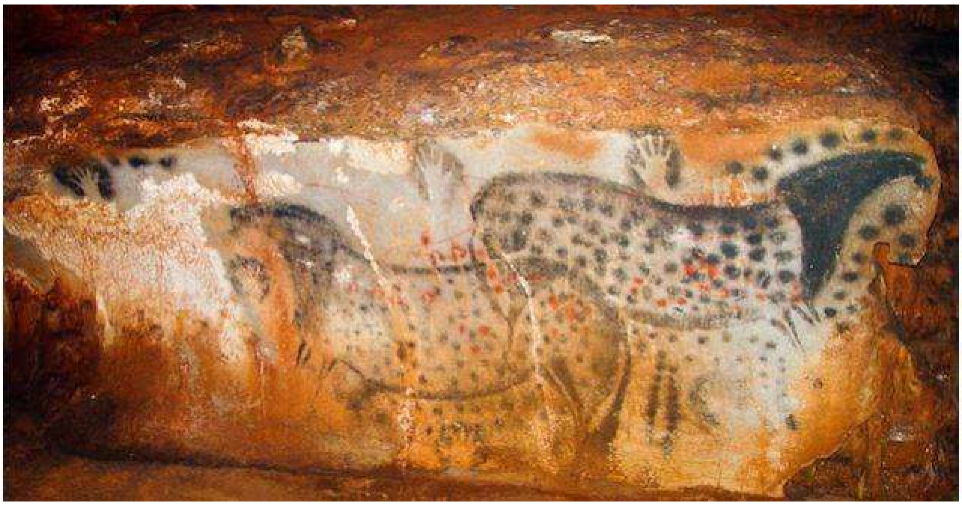

Figure 3.1. Hands as signatures in the cave of 'Pech Merle', near Cabrerets, southern France. Image from France-Voyage.com.

The importance of hand as a symbol of possession and identity is also supported by the use of its representation in proto-writing systems, like in a Sumerian clay tablet of the IV millennium B.C. (Fig. 3.2)

Figure 3.2. Sumerian clay tablet with a hand in the upper left corner probably signifying possession of the other represented things. IV millennium B.C. Paris, Louvre.

3.1.2 The man is the most intelligent among the living creatures because he has the hands.

The cognitively paramount role of the hand has been conceptualized by the first presocratic philosophers. Aristotle reports: ' Ἀναξάγορας μέν οῦ̃ν φησί δῐά τό χεῖρας ἔχειν φρονεμώτατον εἶναι των ζωών ἄνθροπον' (Diels, 1974), that is: '*Anaxagoras indeed said that among the living creatures, the man is the most intelligent because he has the hands*'. Curiously this sentence, which seemed inaccurate to Aristotle, because in his view brain evolution should have preceded hand evolution, has been demonstrated correct by a major discovery in Tanganika. There, in 1959 and following years, rather evolute stone tools at least one million year old were discovered together with bone remains of a 'man-ape' named 'Zinjanthropous'. Bones of hands and a skull were retrieved at the same site, obviously connected with the tools. What surprised the scientists was the finding that the hand bones suggested a close similarity to the anatomical features of the hand of the contemporary Homo Sapiens, whereas the brain skull indicated a much smaller brain (Napier, 1962). This meant that the hand evolved much earlier than the brain, indicating that possibly evolution of hand induced evolution of the brain and not viceversa.

3.1.3 Hands create, hands perceive

The hand is a wonderful instrument by which the human being interacts with the environment. Such instrument allows humans to be creative in shaping materials, but to do so, it has to convey haptic information about its own state, and the state of the environment around. Together with vision, it is the most important sensory instrument of human beings. Sensory nervous fibres from the hand, after two intermediate relays, end up in a comparatively vast area of the parietal brain cortex, the so called "primary sensory area" which, together with the lips, is the largest represented part of the body on the cortex (Rizzolati and Kalaska, 2013). Such representation has been mapped in the 'sensory homunculus' (Penfield and

Rasmussen, 1950), which is a distorted human figure, with enormous hands, face and lips (Fig. 3.3 on the left).

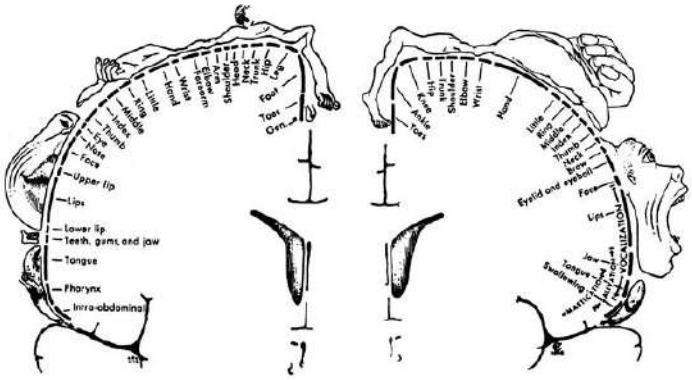

Figure 3.3. On the left is the sensory homunculus and on the right is the motor homunculus From Penfield and Rasmussen (Penfield and Rasmussen, 1950).

The homunculus provides a visual impression of the enormous relevance that sensations from the hand play not only for everyday living activities, but also for more exclusively cognitive uses, as writing, drawing and in general, creating new, useful things. Information on the hand about its position, muscle effort, movement, superficial and deep touch, in a word haptic information (Hasiao and Bensmaia, 2007), represents an essential part of the process leading to programming movements aimed at a creative task. On the motor side, another homunculus, a motor homunculus mainly representing fine movements of the hands and lips resides on a strip of cortex facing the sensory homunculus, a testimonial of the importance of the hand as a creative instrument (Fig. 3.3, right). Observation about the hand motor and sensory capacities have always been empirical until neuroscience progressed into its 'functional' phase, that is the study of the working nervous system in the normal intact human subject. Such progress started in the 1800s, but had its great steps forward in the 1900s and in the first years of the current century, thanks to the electroencephalogram (EEG), positron emission tomography (PET), computerized tomography (CT), nuclear magnetic resonance (NMR), functional nuclear magnetic resonance (fNMR) and functional transcranial doppler (fTCD) (Bartolini et al., 1996; Duschek and Schandry, 2003; Freeman and Quiroga, 2013; Muehllehner and Karp, 2006; Poldrack, 2012; Shakeel et al., 2015). Whilst the EEG directly measures the electric fields generated by neuronal activity, all the other techniques only provide information about the blood supply, which is expected to be roughly proportional to the amount of the excited neurons, hence it is an indirect measure of their activity. All such studies could be performed in healthy subjects carrying out cognitive or very simple tasks and identifying the most involved areas of the brain cortex for any given function.

These discoveries gave strong support and inspiration to essays like those by J. Pallasmaa and other architects, advocates of the importance of senses other than vision, and especially the sense of touch, in creating and enjoying architecture. In his introduction to the 'Eyes of the skin' Pallasmaa states: *'The computer is usually seen as a solely beneficial invention, which liberates human fantasy and facilitates efficient design work. I wish to express my serious concern in this respect, at least considering the current role of the computer in education and the design process. Computer imaging tends to flatten our magnificent, multi-sensory, simultaneous and synchronic capacities of imagination by turning the design process into a passive visual manipulation, a retinal journey. The computer creates a distance between the maker and the object, whereas drawing by hand as well as working with models put the designer in a haptic contact with the object, or space. In our imagination, the object is simultaneously held in the hand and inside the head, and the imagined and projected physical image is modelled by our embodied imagination'* (Pallasmaa, 2012). After decades of growing enthusiasm towards the computer aided design (CAD), which implies just an input of data via keyboard and mouse, its limitations are now felt by several architects and illustrators, with strong concerns (Scheer, 2014). In CAD design the hand movements are very much limited, quite the opposite situation than the freehand drawing. Such difference in motor activity may affect the birth of novel ideas. This notion is strongly supported by current evidence that voluntary movements of the hand nurture creativity through several mechanisms within the nervous system.

3.1.4 Brain functions and creativity: the electric maze

Psychological studies on creativity have been fostered since the middle of the last century, and several definitions have been proposed, but today most scholars will agree that creativity is a mental process that "involves the production of novel, useful products", the products being, of course either tangible, like crafts, or not tangible, like ideas (Mumford, 2003). The most important mental process at the basis of creativity is considered to be the divergent thinking (Guilford, 1956), where the subject explores several solutions to a problem in a short time (Fig. 3.4). As a result only one solution is chosen, often without rational basis, and the solution is then reinforced and better organized through the subsequent convergent thinking (Guilford 1956).

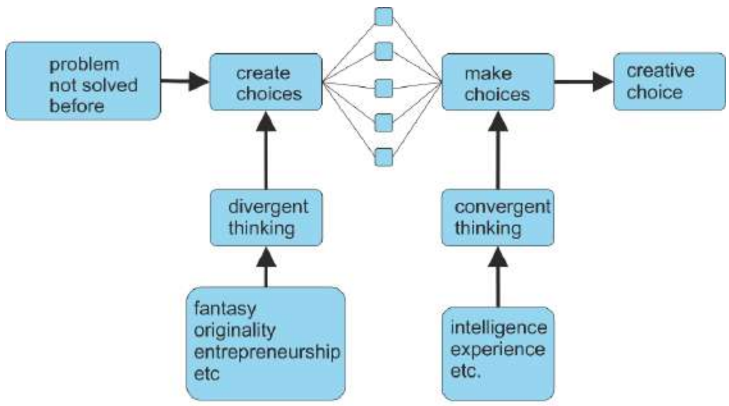

Figure 3.4. Flow chart of divergent and convergent thinking, the bases of creativity. Flowchart by the author.

The above process well adapts to the dynamics of the act of drawing, where at each movement the author faces a number of possibilities, like direction of the pencil, pressure, inclination, thickness of the trait; among them, without rational thinking, and mostly instinctively, the decision is quickly made, apparently by the hand itself. Of course the question arises about the neural substrate of such mental process that commands the hand. The brain cortex is obviously involved, but so far there is no definite evidence about the cortical areas which may give rise to creativity. Although it is recognised that creativity is a psychological process stemming out from ubiquitarian activity of the brain cortex, some cortical areas of the brain cortex have been hypothesised to be more important than others. These are the supplementary and presupplementary motor areas (Fig 3.5), in front of the primary motor area where direct commands to the hand muscles are originated (Nachev et al., 2008).

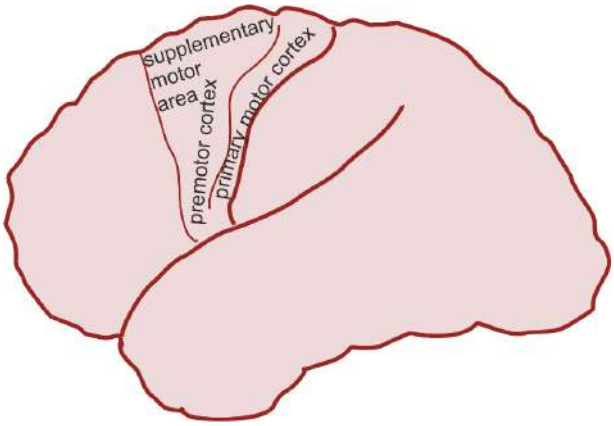

Figure 3.5. Cortical areas, with the supplementary motor cortex, which includes the presupplementary area. Drawing by the author.

It is worthy noting that nearby, in the premotor cortex, "mirror neurons" (Kohler et al., 2002) have been found (Fig 3.6).

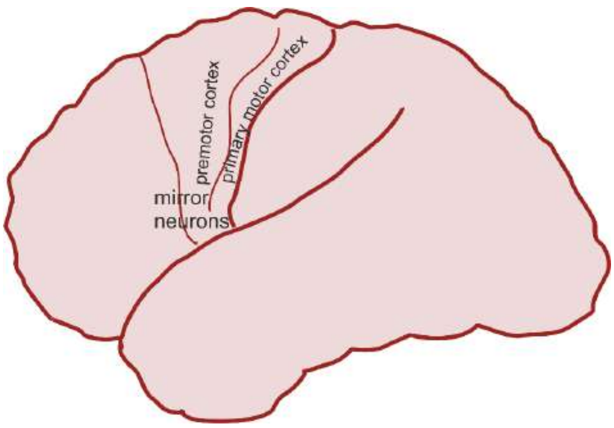

Figure 3.6. Cortical areas with mirror neurons. Drawing by the author.

These are intrinsically ambivalent, as they behave like motor neurons but also are activated by sensory impulses. Because of this property they are thought to play a key role in creativity (Matheson and Kenett, 2020). What is most important, this area receives strong connections from the parietal cortex, which is the main brain centre dedicated to processing the meaning of sensory afferents (Rizzolati and Kalaska, 2013) (Fig. 3.7).

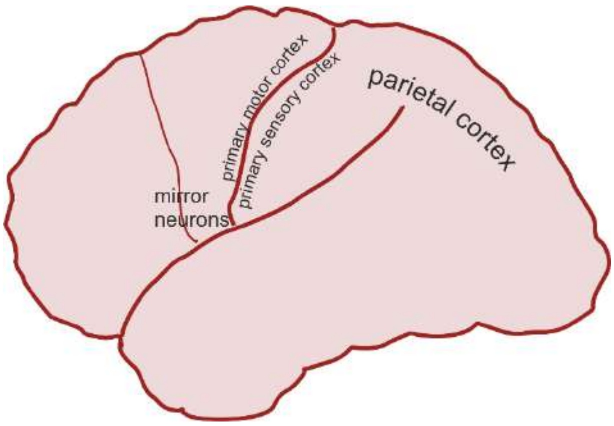

Figure 3.7. The parietal cortex is devoted to receive and process sensory afferents. Drawing by the author.

Besides the above areas, the role of the cerebellum, has also been claimed to play a definite role (Vandervert et al., 2007). It is of some relevance that both the frontal lobes and cerebellum are neural centres for origin and control of movements. On one hand, the frontal lobes develop the intention of movement, its organization and decide the rate of its speed and tune high precision movements, for example those of fingers. On the other hand, the cerebellum ensures that the orders from the frontal lobes are correctly and smoothly executed, coordinating all muscles concurring to the movement, as some of them have to contract, others have to give way. In addition to that, both neuroanatomical studies in animals and neuroimaging in humans, performed around the turn of the century, demonstrated that the cerebellum is not exclusively dedicated to motor control, but also is an important structure for cognitive function, with connections to all of the cognitive relevant areas of the cerebral cortex (usually called associative areas) (Buckner, 2013) (Fig. 3.8).

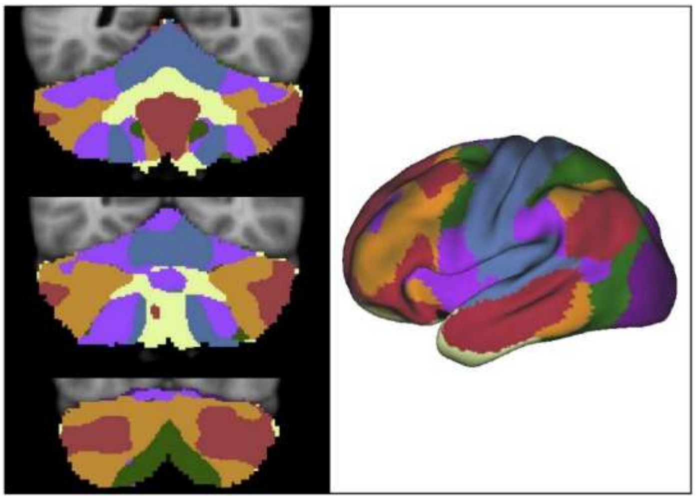

Figure 3.8. On the left are some sections of the cerebellum. Coloured areas of each cerebellar section are connected with cortical areas labelled with the same colour shown on the right. Large parts of the parietal and frontal areas are connected with the cerebellum. From Buckner (Buckner, 2013).

In conclusion, having ascertained that the frontal lobes and the cerebellum, which are the most relevant neural structures implicated in movement, play also an important role in a variety of cognitive functions, it is possible to surmise that they may be implicated in a possible mechanism of creativity stimulated by the movement itself. However, it is worth reminding that complex cognitive functions like creativity are the result of many mental constructs, on their turn influenced by a large amount of variables, most of them still unknown (Sawyer, 2011), Also there is the complexity due to the multifunctionality of cortical areas, to which plasticity should be added. Correlation between cerebral areas and cognition, therefore, is not straightforward and cannot be restrained to linear deterministic processes. This is particularly true for creativity, one of the most complex cognitive functions. So, the quest for experimental evidence about creativity is far from straightforward. It should be endeavoured by posing simple questions, with as little amount of variables as possible, with answers based upon the most direct parameter linked to neuronal activity: the generated electrical field.

3.1.5 The nervous tissue generates electrical fields recordable from the surface of the body

The aim of the nervous system is to transmit information, in its broadest possible sense. This is done by electric pulses. The main functional component of the nervous system is the neuron, a biological cell bounded by an excitable membrane. In its resting state, the membrane has properties that keep the inside of the cell at a negative electrical potential relative to the outside at approximately -80 mV. When the cell needs to transmit information the membrane changes its state from resting to excited by reversing the electric potential difference, which now turns to positive inside (approximately +30mV) and negative outside (Hodgkin and Huxley, 1952).

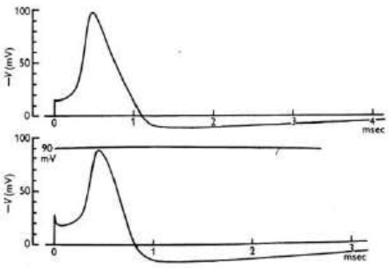

Figure 3.9. The action potential generated by depolarization of the axon membrane. The graphs show the differential potential across the membrane. When the membrane is activated, the inner potential from -80mv at resting state (time 0) goes up to + 30mV. From Hodgkin and Huxley (Hodgkin and Huxley, 1952).

This change of polarity lasts only a few milliseconds, but it triggers the same process an the nearby membrane segment, so it moves along and its state is transmitted to the other end of the nerve cell, where it may encounter another excitable membrane to which pass the information. The temporary change in polarity may be regarded as an electric pulse conducted at a slow velocity across biological structures by means of a biophysical process. In humans, the conduction velocity along peripheral nerves, either motor or sensitive is in the range of 50-80 m/s approximately (Buchthal and Rosenfalck, 1966).

The generated electric field can be recorded not only from the surface of the nerve fibre, but also detected by an electrode placed at some distance in the outside conducting medium, with voltage inversely proportional to its distance from the source. The voltage thus produced at the electrode by only one neuron is extremely small, fractions of microvolts, and cannot be recorded from the surface of the body. However, when hundreds or thousands of neurons are activated in a restricted period of time, the pulse-generated electric fields may be of sufficient phase concordance for an effective summation to provide a potential large enough to be detected from the skin surface. This way, clusters of neurons in the cerebral cortex are rhythmically activated in a synchronous manner and generate the activity detected at scalp level that is commonly known as the electroencephalogram.

3.1.6 Spontaneous activity of brain cortical neurons: the Electroencephalogram (EEG)

The electroencephalogram was first recorded from the intact skull (Fig 3.10) by Hans Berger, who published the results in 1929 (Berger, 1929) and coined the term *Electroencephalogram* abbreviated in EEG. The recording of these electrical potentials was difficult when first introduced, but soon progress in electronics made it affordable in clinical laboratories worldwide. The usually recorded EEG only reflected the *spontaneous* activation of cortical neurons, unrelated to the perception of any external stimulus.

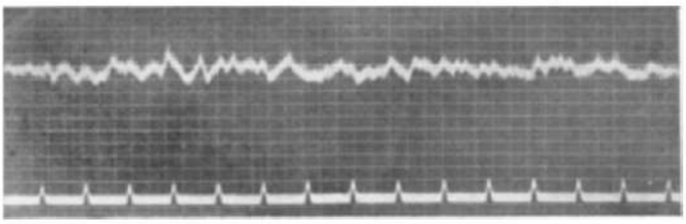

Figure 3.10. The first EEG recorded by H. Berger. The EEG is depicted in the top trace; the bottom trace represents the 200 ms time marker. From (Berger, 1929), Fig. 1.

3.1.7 The cortical response to a peripheral stimulus: the Evoked Potential (EP)

Approximately two decades later a paper was published reporting the occurrence of an EEG response after electric stimulation of peripheral nerves (Dawson, 1947). From experiments in animals and subjects affected by certain forms of epilepsy, it was already known that a peripheral stimulus could evoke a response at the cortical level, but its amplitude in healthy human subjects was so small that it could not be detected from the surface of the scalp amidst the much larger spontaneous EEG. That first experiment by Dawson was performed with the technique of photographic superimposition. The EEG trace was displayed on the screen of an oscilloscope and a photograph taken in synchronism with the stimulus. Only those EEG events locked to the stimulus would superimpose and make an enhanced signature on the film, whilst those randomly occurring would just contribute to the background blur (Fig.3.11).

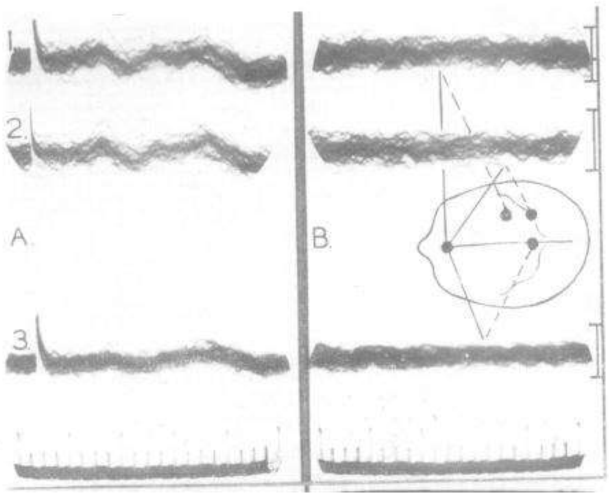

Figure 3.11. In A oscilloscope EEG traces time locked to an electric stimulus at the ulnar nerve have been superimposed on film; in B are shown EEG traces not locked to a stimulus. In A there are definite deflections, indicating that a part of the cerebral activity was evoked by the stimulus, whilst in B there are just blurred tracings due to the spontaneous EEG activity. From Dawson (Dawson, 1947), Fig. 1.

Later on, a more rigorous approach was used by implementing the statistical averaging method with an electronic apparatus (Dawson, 1954), thus obtaining a much better defined signal of the evoked response. Differently from other statistical techniques aimed at improving the signal to noise ratio, like autocorrelation and crosscorrelation, the averaging method has the double advantage of maintaining the original signal waveform and of simple hardware implementation (Hassan and Anwar, 2010). Recording the EEG responses after peripheral stimuli was soon a technique that permitted to explore several sensory pathways and, at a time when modern neuroimaging was yet to come, this was one of the diagnostic mainstays in neurology

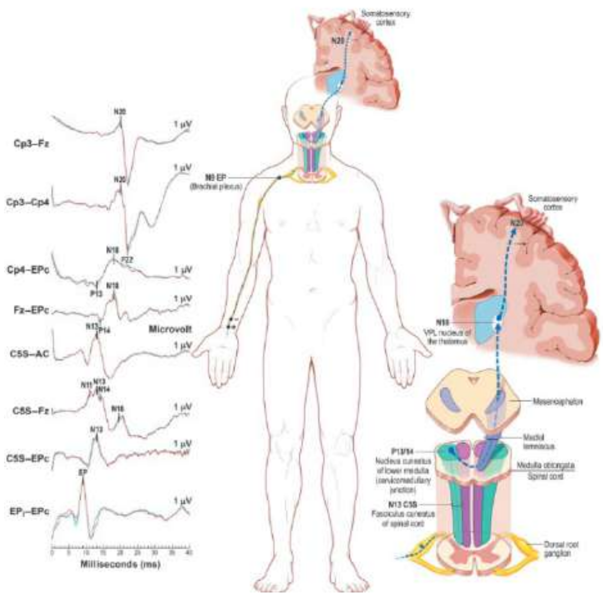

Figure 3.12. Examples of somatosensory evoked potentials (SEPs) recorded from the surface of the body at various positions, after stimulation of the median nerve at the wrist. From Muzyka and Estephan (Muzyka and Estephan, 2019).

It was bound to be a research subject on its own, which was named *evoked potentials* or EPs. According to the peripheral part of the nervous system that was stimulated, the acronym EP was preceded by a letter; for example, when the sensory peripheral nerves were stimulated, the resulting EEG response would be labelled SEP, after the adjective *somatosensory*, or VEP after *visual*, and so on. Since then a large amount of literature has been published reporting assessment of the function of sensory systems in the healthy physiological state and in many neurological affections. However, this successful methodology was limited to the study of nervous pathways that could artificially be activated at the peripheral end and terminated at the brain, so only afferent sensory pathways were explored. Given that the averaging technique was so successful, it was natural that some researcher could dream of exploring the motor efferent connections by using the same principle. The difficulty lay in the fact that the start of that pathway was normally unaccessible, being the brain itself. The other end was instead very easily accessible, anatomicaly and functionally, as the muscle activity generates large electrical signals recorded by electrodes at the skin surface, also known as surface electromyogram (EMG).

3.1.8 The cortical activity before movement: the Bereitschaft Potential (BP)

So, assessing the function of the motor pathway related to spontaneous movements needed a different approach than the cortical responses evoked by peripheral stimuli. In the sensory pathway the signal to analyse occurs after the stimulus, which triggers the acquisition of the EEG period of interest, an easy task to accomplish. But to investigate the movement related brain activity, it was necessary to start with the triggering event (the movement) and go back in time to the brain activity occurring before it. In a pre-computer era such performance could only be carried out by recording on magnetic tape the EEG together with the triggering signal provided by the EMG, and then running the tape backwards, so that the trigger signal would take place before the EEG event. At the conference held in Berlin to commemorate the 50th anniversary of the first recording of the EEG preceding movement, Lüder Deecke (Deecke, 2014) remembered how the idea of the 'back averaging' was born while he, a PhD student, and his mentor Hans Helmut Kornhuber discussed the matter in a beautiful garden, 'at the foot of the Schlossberg hill in Freiburg, Germany'. Their successful experiments were finally reported in a paper describing a negative going long lasting wave, that preceded the movement starting approximately between 1 and 1.5 seconds before, and reaching a maximum amplitude of 10-15 uV approximately 60-90 ms after the actual movement (Fig. 3.13).

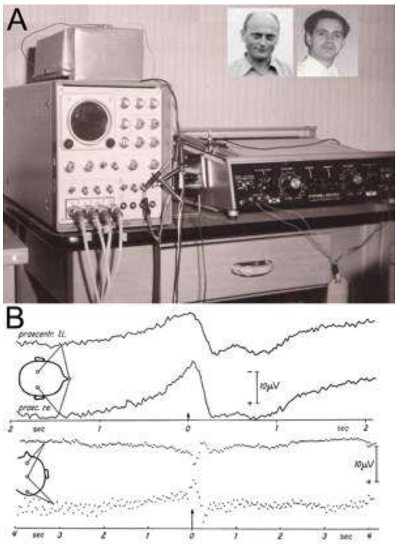

Figure 3.13, The equipment used by Kornhuber and Deecke for their first experiments, and the Bereitschaftspotential. From Deecke (Deecke, 2014).

Such wave was called Bereitschaftspotential or Readiness Potential and abbreviated as BP or RP (Kornhuber and Deecke, 1965a); they also observed that it was increased with intentional engagement and reduced by indifference on part of the subject. It was followed by some waves occurring after the movement, called 'reafferent evoked potentials', which reflected the sensory activity evoked by the voluntary movement (Bates, 1951). In that first set of experiments the subjects were requested to perform simple spontaneous movements at irregular intervals, like pressing a button, squeeze a rubber ball or pull a line. Speed of movement was checked for consistency. The number of movements needed to record a reliable cortical activity was between 100 and 500. This pioneering article opened the door to a huge research on the EEG locked to spontaneous movements. Of course, one of the main questions that ought to be answered was the origin of the recorded waves. Since that first work (Kornhuber and Deecke, 1965a), the authors found that the readiness potential preceding movement was larger over the hemisphere contralateral to movement, something to be expected given the crossing of the motor pathways. They also found that within the hemisphere the amplitude was larger at the central and frontal areas, smaller at the occipital site. This finding was in accordance with the known function of the frontal part of the cerebral cortex (Fig.3.14), dedicated to planning intentional movements and to generating signals aimed at muscle control through the corticospinal tracts (Kalaska and Rizzolati, 2013). Further research assessed that the BP was mainly originated bilaterally in the supplementary motor area, just in front of the primary motor area (Shibasaki, 2012).

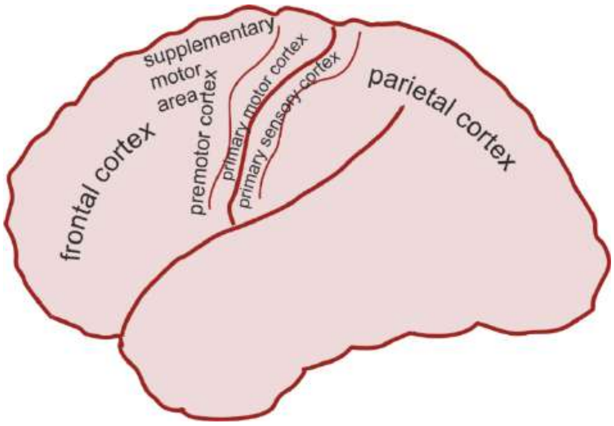

Figure 3.14. The frontal motor cortex, with the primary area, providing direct signals to the spinal motor neurons, the supplementary motor area and the premotor cortex. The slow component of the BP is probably originated in the supplementary motor area. From Kalaska and Rizzolati (Kalaska and Rizzolati, 2013), p. 840.

However, the part of the BP chronologically most close to the movement, also called motor potential or MP, was originated by the primary motor area (Fig. 3.14) (Shibasaki, 2012). Many types of movement have been tested, with the large majority assessing simple repetitive movements implicating hand or foot, and performed during various tasks (Shakeel et al., 2015; Shibasaki, 2012). The need of a precise triggering pulse has usually limited the possibility of exploring complex movements, thus excluding the analysis of movements resembling everyday activity. In a review reporting research on cortical responses related to learning and executing motor skills, it was remarked that the majority of studies on movement related potentials lacked '*ecological validity*', meaning that the experiments were carried out in unnatural conditions, so their contribution to the understanding of the actual mechanisms related to a naturally complex motor activity was limited (Wright et al., 2011). One of the characteristics of the movements that we perform in real life, interacting with the environment, is that they are fast and often repeatedly executed, sometimes with a precise rhythm, in sharp contrast with the BP recordings, where intervals of at least 5-10 seconds were required between movements (Kornhuber and Deecke, 1965a). This observation prompted some authors (Gerloff et al., 1997; Kopp et al., 2000) to investigate the EEG in a 'steady state' condition, during fast repeated finger action. The target of the first study (Gerloff et al., 1997) was to record pre and post movement peaks (pre- and post-MPs) during movements performed at the rhythm of 2/s. The long duration BP could not be investigated because of the short time period involved, with an analysis time of just 300 ms before and 200 ms after movement. Taking as reference the start (onset) of the electromyographic activity at the forearm extensors, the pre-MP was a negative deflection occurring at approximately -60 ms (the minus sign stands for a time mark preceding the movement) at the contralateral parietal electrodes, while the post-MP was a negative deflection seen at the contralateral frontal electrodes peaking at approximately 90 ms. The authors concluded that the pre-MP was predominantly generated in the primary motor cortex (M1) and the post-MP in the primary sensory cortex (S1) (Fig. 3.15). The two peaks should reflect the motor efferent and sensory afferent volleys taking place during rapid movements. Such features are expected to be seen in any experiment implying rapidly repeated movements.

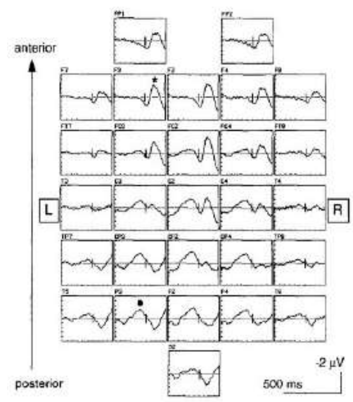

Figure 3.15. Recordings of pre- and post-movement peaks (MPs) related to fast repetitive movements. The filled circle marks the peak of pre-MP and the asterisk that of post-MP. From Gerloff et al. (Gerloff et al., 1997).

One of the few papers with BP recordings in actual circumstances involved pianists who were asked to play a note and a short melody (Kristeva, 1984). It was found that the BP recorded at the start of a complex melody had a larger amplitude than a simple note and was spread to larger cortical areas, suggesting that a difficult motor task would involve more cortical areas than an easy one. However, it appears that very little has ever been published about BPs recorded during spontaneous movements in freehand drawing. Some experiments have been performed on primates, with deep single cell unit recordings direct from the cerebral cortex while the animal traced some lines along a predetermined path (Moran and Schwartz, 1999; Schwartz, 1994). These papers were not concerned with the scalp recorded BP, but aimed at assessing the spatial distribution and temporal dynamics of activated neurons of the primary motor cortex generating the cortico-spinal volley to the upper limb muscles. It could be demonstrated that a neuronal vector (i.e. a spatial sequence of activated neurons) formed up to guide the drawing path followed by the hand. Such interesting experiments, however, could not be replicated in humans for their invasiveness. Handwriting was another subject of BP related investigations which, at least in one occasion, was studied together with execution of elementary drawings (Schreiber et al., 1983). It was found that the BP started before and was larger in amplitude when recorded at the start of writing or drawing than when a meaningless scribbling was performed. In general, the large majority of the papers dealing with BPs were concerned either with the source of the single components (Shibasaki, 2012), or with the subject of the free will long since debated by philosophers (Deecke, 2014; Libet et al., 1993; Schurger et al., 2012), and, of course, with impairment due to neurological conditions (Dick et al., 1989; Schurger et al., 2012; Shibasaki, 2012; Shibasaki and Hallett, 2006; Van Der Kamp et al., 1995).

3.1.9 The BP as correlate of neurocognitive activity before movement

So, this first phase of research on BP mainly focused on cortical activity in preparation of comparatively simple movements; only recently the cognitive processes of action forethought have been investigated (Di Russo et al., 2017). In neuropsychology, praxis is a cognitive process and defined as the ability of performing skilled or learned complex movements finalised to a definite aim (Kriegstein and Brust, 2013) and implies planning of action on the part of several cortical areas (Fig. 3.16). All our actions are performed in response to inner thoughts or to stimuli from the environment; from these early steps, the will of movement is born and the motor plan is started to form up. So, a series of experiments have been directed to understand praxis (the ideation and planning of movement) rather than just simple motor commands. When asked to perform cognitively demanding tasks, the investigated subjects produced cortical activity very similar to the previously known BP, but starting much earlier, approximately 3 s instead of 1.5-2 s before the actual movement. Such activity was localised both in the prefrontal and also in the posteriorly situated parietal area. It could be demonstrated that such activity was specific of complex praxic actions (Bozzacchi et al., 2015; Wheaton et al., 2005). Interestingly, the very early activity which occurred in the prefrontal areas was modulated by an emotional expectancy state, whereas the traditional BP was not (Perri et al., 2014). These studies on neurocognitivity, however, have the drawback of long intervals between movements, thus falling in the same category of unnatural movements as the previous studies on BP.

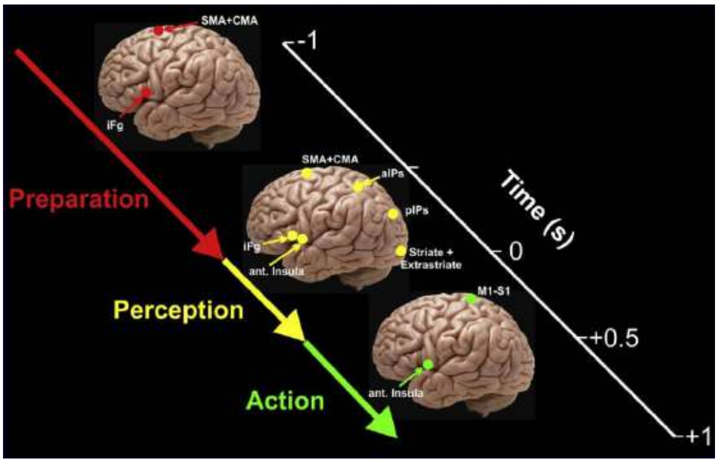

Figure 3.16. The cortical areas sequentially activated in the process of movement ideation and preparation according to recent neuropsychological evidence and hypotheses. From Di Russo et al. (Di Russo et al., 2017), Fig. 15.

3.1.10 The EEG before and after movement: the movement related potential (MRP).

Most of the attention of the EEG recording relative to movements has been focused on the period preceding the muscle activity leading to motion. The acronyms BP or RP have been used to identify the components in that epoch and often to indicate the whole of the brain activity related to movement. However, the brain activity following the movement has been named *as* 'reentrant potential' (Kornhuber and Deecke, 1965a) or 'post-movement potential' (Gerloff et al., 1997). The current trend is now to call the whole movement related brain activity as Movement Related Potential (MRP) and to differentiate between the events preceding or following movement labelling them as pre- or post-movement events or components (Shibasaki, 2012).

3.1.11 The limited role of magnetoencephalography (MEG)

When neurons depolarize, the ionic currents not only generate an electric potential which is recordable as EEG, but also a magnetic field of extremely low intensity of the order of femTeslas (10^{-15} T) (Baillet, 2017). Nevertheless, such tiny fields generated by brain neurons can be detected at the surface of the scalp with sophisticated equipment featuring sensors based upon the superconducting quantum interference device (SQUID) (Fig.3.17).

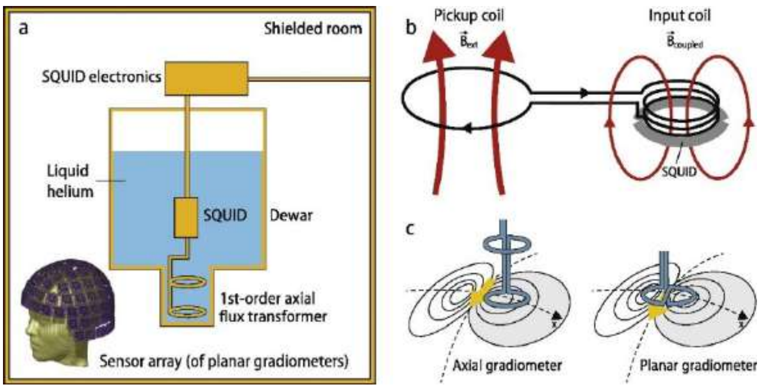

Figure 3.17. Schematic of a SQUID magnetometer set to record MEGs from the scalp. From Baillet (Baillet, 2017).

Such sensors do not need physical contact with the scalp, which is one of the advantages of MEG on the EEG, where instead a troublesome session of electrode placement is needed before each recording. But the most important advantage of MEG is that the magnetic field is only dependent on the distance between source and detector, and is not affected by the interposing biological media (nervous tissue, vessels, blood, liquor, bone, skin) which are the most relevant distortion factor for the EEG recorded electric field. Due to absence of such distortions, it is possible to identify with precision the source of MEG recorded activity, which is very difficult in the case of the EEG (Baillet, 2017). Both EEG and MEG have excellent time definition and for such reason these are the only two techniques that may assess the temporal relationship between sequential cortical events, like the Bereitschaft Potential (BP), the Movement Related Potential (MRP), and Evoked Potentials (EPs). Several studies have been performed on BP and MRP using MEG in the attempt to identify the source of single deflections (Erdler et al., 2000; Gross et al., 2005; Kristeva, 1984; Kristeva-Feige et al., 1997) confirming that the supplementary motor area and the primary motor area are the main sources of the slow early negativity of BP and of the late negative-positive deflection that follows it (Deecke, 2014). With all its advantages, the MEG is still a little used technique, mainly because it needs extremely sophisticated and costly equipment, which has limited its use to experimental research only. Besides, the smallness of the recorded signal seems to limit its detection ability mainly to magnetic fields of radial orientation relative to the brain centre. For such reasons, the papers on MEGs and movement related potentials are very few.

3.1.12 Functional neuroimaging techniques other than EEG and MEG.

Whilst EEG and MEG directly record the neuronal electric discharge, other methods rely on indirect assessment of neuronal activity, based upon the principle that neurons change their metabolic state when they fire and consequently the regional cerebral blood flow (rCBF) increases . Positron emission tomography (PET) was the first of non invasive techniques that could monitor the cerebral blood flow or neuronal metabolism (Fan et al., 2020); it implies the intravenous injection of a radioactive tracer to accomplish its task, so it is not entirely innocuous; besides, its temporal resolution is low, in the order of minutes and it is highly expensive. Because of these limitations, it is seldom used in cognitive neuroscience. Functional magnetic resonance imaging (fMRI) measures the oxygen in excess that pervades activated cerebral regions. When oxygen demand by firing neurons is increased, the reflexly increased blood flow supplies more oxygenated hemoglobin (oxyhemoglobin) than is actually needed, so just a fraction of it releases oxygen converting to deoxyhemoglobin. The excess of oxyhemoglobin can be detected with MRI because of its magnetic property and acts as a contrast medium for the whole hyperoxygenated area. This technique has very good spatial definition, but the fact that it measures a hemodynamic response that takes time to build up does not allow to assess a precise time sequence of the neural events. It has the great advantage of being innocuous and not needing any injected contrast medium . For such features, it is by far the most used technique in functional neuroscience (Fig. 3.18), though sometimes its performances may be overrated (Poldrack, 2012).

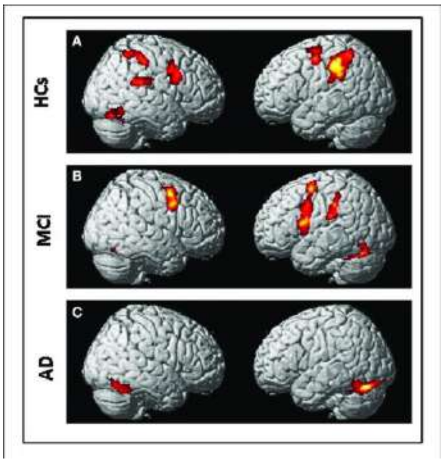

Figure 3.18. Images of increased blood flow in the cerebral cortex following hand movement and observation of hand in normal (A) and cognitively impaired subjects (B and C). Activated areas are present in the occipital, parietal and frontal cortex. Spatial localization is quite detailed, but there is no information about time occurrence of the phoenomena. From Farina et al. (Farina et al., 2017).

Another instrument to assess the hemodynamic reflex locked to hyperactive neurons is the near infrared spectroscopy (NIRS). Progress in equipment has recently allowed to measure the infrared absorption of the cortical superficial layer even through the intact skull. It features poor localization in its native form, but a higher precision is available through the event related optical signal (EROS) method (Gratton and Fabiani, 2001). It has seldom been used so far.

3.1.13 Haptic perception detected by SEPs and ERPs

As mentioned above, the BP or MRP denominate the time period of the EEG preceding the movement. The period occurring after that pertains to the so called Somatosensory Evoked Potentials (SEPs). The sensory activity, from the first arrival to the primary sensory cortex, up to its dissemination to associative areas where the meaning of the perception is analysed and transformed into ideas, can be detected by means of the cortical Somatosensory Evoked Potentials (SEPs). These are electroencephalographic responses recorded from the scalp at locations over cortical areas and time locked to a stimulus of electrical or mechanical nature suited to activate somatosensory fibres sensitive to skin touch or movement of muscles or joints of the limbs (Muzyka and Estephan, 2019). It is well known that the early part of the SEP is the reflection of the first arrival of the sensory volley on the parietal cortex (primary sensory area) and related to the characteristics of the stimulus only (Fig. 3.19).

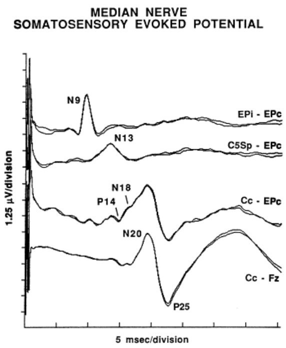

Figure 3.19. After stimulation of the median nerve at the wrist, the first cortical activity is the peak of N20, a component that is not dependent on cognitive functions. From Desmedt et al. (Desmedt et al., 1983)

Further components are due to subsequent cortical processing and dependent on the level of cognition related to the stimulus (Desmedt et al., 1983). A series of SEP peaks (or components) have been identified following stimuli brought to the hand; they have been named according to their polarity (positive or negative) and to the time in milliseconds (ms) expired between the stimulus and their appearance on the recording (such interval is named “latency” in neurophysiological jargon). The best known components recorded on the scalp over the parietal area contralateral to the stimulated limb are the following: N20, P40, N60, P100, N140, P300 (Fig. 3.20).

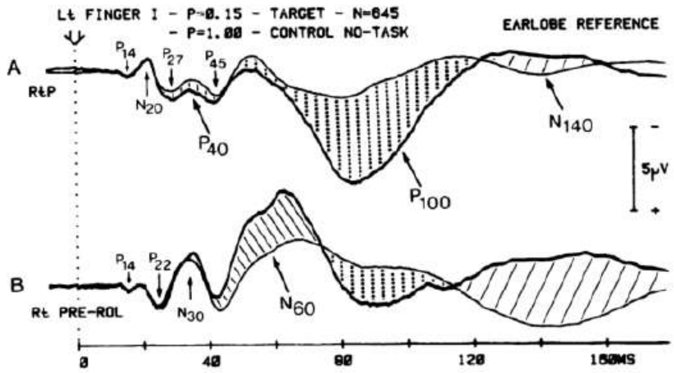

Figure 3.20. SEPs recorded from the sensory (A) and motor (B) areas contralateral to the stimulated hand. Dashed areas mark the difference between late components (following the N20) that are more or less affected by cognitive conditions and period of stimulation. It is very obvious how the N20 is not affected. From Desmedt et al. (Desmedt et al., 1983).

While N20 is the activity from the primary sensory area, all the others are from associative areas and influenced by cognitive functions. The different properties of this class of components starting from P40 prompted neurophysiologists to call them also “event related potentials” (ERPs), meaning that there is not a proportional link to the stimulus (for example, the larger the stimulus intensity the larger is the response amplitude, as for the N20), but that they are just more or less loosely “related” to the stimulus because most of their parameters, like latency and amplitude, are mainly due to brain processing (for example amplitude of such components is dictated by attention but not by stimulus intensity) (Luck, 2014).

For such reasons, the ERPs have been exploited to investigate the subjective reactions to stimuli during psychologically relevant tasks (Luck, 2014)..

3.1.14 Summing up

In order to explore the sequence of events that take place in the different cortical areas in response to a definite event it is mandatory that the method used has a high time definition, of the order of one millisecond or less. So, the only easily available method is the EEG (and the EEG based techniques like MRPs, before movement, and SEPs or ERPs, after movement). Its spatial definition is limited, but if such feature is not the goal of the research, the offered advantages greatly overcome the drawbacks. The EEG is unexpensive both as equipment and consumables; it is completely safe and very well tolerated, especially if just few electrodes are used. The subject may forget bearing attached electrodes, and so it is ideal for *ecological* experimental sessions, where movement should not be restrained. The signal is small, but with the averaging technique it is possible to enhance the signal to noise ratio. And last but by no means the least, the EEG has been the most widely used technique to record MRPs, SEPs and ERPs, so by using such technique, it is easy to compare new experimental results with the published literature.

3.2 Aims of the three experiments on freehand drawing and creativity

Creativity is an extremely complex cognitive function and it would be preposterous to seek an hypothetical brain activity correlating with creativity. The very notion of creativity seems to escape rigid frames, although there is a general agreement on some prevailing fundamentals for a cautious definition as a mental process that *'involves the production of novel, useful products'* (Mumford, 2003). So, the quest for scientific evidence on the hypothesis that freehand drawing can boost creativity may look an impossible one. Nevertheless, complex problems may be solved if disassembled into simpler parts to be tackled with feasible techniques. It should be possible to focus the investigation just on factors acting as elements reputed necessary to creativity, but depending on elementary variables that are controllable. The recording of the electroencephalogram is a simple technique that perfectly complies the necessity of accurate timing, which is a mandatory characteristic of the system to be used for this investigation. Furthermore, the study of the EEG during movement is feasible as long as the movement elicits a trigger signal, which also is a parameter simply obtainable. Following the working hypothesis, a variable that can be introduced in this paradigm is the sort of hand movement. One type could be the freehand drawing with a stylus, with no constraint. The other could be the inputting of coordinates of a design with a mouse. The expected outcome is a difference that should be found between the two tests either in the pre- or in post-movement EEG epochs, that is the MRPs on one side and the SEPs and ERPs on the other. Such difference could suggest an involvement of cortical neurons depending on the performed test (freehand versus mouse) possibly linked to the cognitive significance of the movement. With these set premises, the following experiments were planned:

3.2.1 The setting up of the technique

All experiments (1, 2 and 3) have been performed at the Laboratory of Clinical and Experimental Electrophysiology of the Department of Neuroscience, Rehabilitation, Ophthalmology Genetics. Maternal and Child Health (DINOGMI) of the University of Genova, Italy, by the PhD student and her tutors and cotutors during her stay in Genova. It was necessary to implement a reliable technique to record the EEG and the trigger signal in conditions as natural as possible during freehand drawing. This step was unavoidable, as at the time where this research started there were no reports of such recordings during natural drawing movements.

3.2.2 Recording of potentials preceding the movement, the motor side

Once the technique was validated, the recording of MRPs preceding and following each movement would be performed in the two following conditions: in Task 1 the subject would be asked to use a freehand drawing with a stylus and digital drawing tablet as if using a pencil on paper. The use of an advanced raster software and up to date hardware would ensure a close imitation of drawing with pencil and paper. In Task 2 the subject would use a vectorial graphic software and the coordinates would be input with the use of a mouse.

3.2.3 Recording of potentials following the movement, the sensory side.

The third experiment would concentrate on recording the electroencephalographic correlates of perception originated from skin, joint and muscles of the drawing hand while performing the same two tasks required for investigating the motor side.

3.3 Experiment 1. Movement Related Potentials (MRPs) during freehand drawing on digital tablets.

3.3.1 Materials and methods

The whole setting of the experiments and customization of the pen are shown in Fig. 3.21.

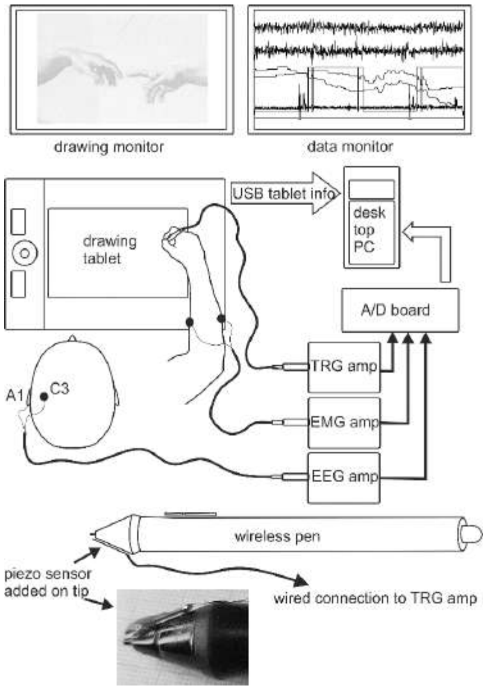

Figure 3.21. Set up of the experiment and customisation of the pen with a piezoelectric sensor. On the drawing monitor an image is presented that the subject has to trace over with pen and drawing tablet, using a raster graphics software that shows the rendering superimposed to the original image. The pen is a wireless device but, as detailed in the lower part of the figure, a piezoelectric sensor has been attached to its tip and connected by wire to the trigger amplifier (TRG amp) and then to the analog to digital conversion board (A/D board) to synchronize with tip contact. To the same board are also connected, after amplification, the EEG and EMG signals (EEG and EMG amp). The tablet receives information from the pen and sends it via an USB3 interface to the computer. All biological and tablet data are shown on a separate data monitor for the operator. In the shown monitor real data are presented; from top to bottom: the EEG, EMG, X and Y coordinates of the pen position, analogic output from the piezoelectric sensor, pen down state, digitized trigger signal from the piezoelectric sensor. In the bottom set a photographic detail of the pen tip is shown, with the piezoelectric sensor securely held in place with two glue drops (From Leandri et al. 2021).

3.3.1.1 Subjects

The recordings were performed on 9 subjects aged 25-35 years, 5 females and 4 males. Handedness was assessed according to the Edinburgh Handedness Inventory (Oldfield, 1971), 8 subjects were right handed and one was left handed. The procedures were totally non harmful and the study was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans. Informed consent was always obtained. All subjects were experienced in freehand drawing either on paper or on digital tablets.

3.3.1.2 Equipment for freehand drawing

An Intuos© PTK-640 tablet (Wacom Co. Ltd., Saitama, Japan) was used with a modified pen. The tablet communicated with the computer via a universal serial bus (USB) interface transmitting information about the status of the pen, like position, pressure and other data. Contact of the pen with the tablet surface generated a trigger signal to be recorded alongside the electroencephalogram (EEG), electromyogram (EMG) and pen parameters in order to synchronize the events occurring before, during and after drawing movements. To obtain a sufficient precision in such timing, the pen was modified by adding to its tip a small piezoelectric sensor (RS PRO M641, RS Components S.r.l., Sesto San Giovanni, Milano, Italy), whose output was amplified with a 4x gain special purpose amplifier for impulsive signals (LT Pulse amplifier and window detector by Vertigo, Genova, Italy) and fed into a dedicated channel of an analog to digital converter board (NI PCIe-6320, X Series Multifunction DAQ, 16 Bit, 250KS/s sampling rate by National Instruments, Austin, Texas). The decision to rely on a signal from the piezoelectric sensor, rather than on the EMG of involved muscles or on the tablet USB output, came from a set of preliminary experiments on synchronization whose results are reported in section 3.3.2.1

3.3.1.3 Drawing sessions

A raster graphics editor (Photoshop ©, by Adobe Inc. California, USA) was used to present on the computer screen a photo of hands on a bottom layer with opacity set at 40%. The subject was asked to draw on a top layer by tracing over the outlines and other relevant particulars of the photo with short strokes. The pen should tap the tablet surface at the start of the stroke and be raised a few millimeters by the end of the stroke. The total number of strokes per each drawing session ought to be no less than 100. The brush tool used on Photoshop was the round hard brush 2-8 pixel dimension. Subjects were asked to draw at a slow pace, leaving approximately no less than a two second interval between strokes. Each subject underwent three drawing sessions alternate with as many tap session (see paragraph 2.4) and each time a new photo was presented, to avoid learning effect or boredom.

3.3.1.4 Tap sessions

A sham condition was tested to check if any difference could be detected between the salient act of drawing and a simple tap of the pen followed by tracing of a line with no specific purpose.

3.3.1.5 The EEG recording

This study was intended to be carried out in conditions as natural and comfortable as possible, so unessential recording leads were avoided. After some preliminary recording sessions it was found that the best positions to obtain short latency pre- and post-motion potentials were those in the central scalp area contralateral to the drawing hand. Recordings were performed from the scalp positions C4 (for left handed) or C3 (for right handed) according to the 10-20 EEG system. The recording electrode was referred to the ipsilateral mastoid. Such reference offered a good compromise between an ideal neutral electrode and interference from activity of the shoulder and neck muscles involved in the drawing movements of the dominant arm. Surface Ag-AgCl EEG cup electrodes (Bionen S.a.s., Firenze, Italy) were attached to the scalp with adhesive paste (Ten20 ©EEG conductive paste by Weaver and Company, USA). Impedance was always kept below 5 KOhm.

Previous papers have shown that the MRP signal is extremely small, of the order of few microvolts (Gerloff et al., 1997; Leandri et al., 2021; Shibasaki, 2012). Because it is recorded simultaneously with the unrelated spontaneous activity of the

EEG which has much larger amplitude, the signal (MRP) to noise (the spontaneous EEG) ratio is very unfavourable. The *noise* components of the recorded activity on the scalp could also originate from other sources than the EEG. originate from many different sources and may be several orders of magnitude larger than the true signal. Firstly, there are signals generated by the activity of head and neck muscles that can be of the order of hundreds of microvolts. Secondly, there are the electrical signals which are not biological in origin, but generated, for example, by the electronic and electric environment, including the EEG amplifiers and the mains power supply; the amplitude of this noise component can be extremely variable, from microvolts to hundreds of millivolts, depending on equipment and setup. All these components may be superimposed in the same recording, so, at first glance, it would not be possible to identify the tiny MRPs hidden by the other much larger signals. However, the MRPs always occur within the same time window in relation to the movement which generated it. If the movement is repeated a sufficient number of times, the simple statistical method of averaging can be applied. It is then possible to decrease the amplitude of random noise components until theoretically cancelling them out, whilst maintaining the time locked part of the true signal, or MRPs (Collura, 1995). In order to detect MRPs in this experiment, approximately 100/300 EEG related movements were averaged. Because of residual large high frequency noise even after averaging, a low pass digital Butterworth filter (20 Hz) was applied off line. The time window used for analysis started 800 ms before movement and ended 800 ms after it, so, in all, 1600 ms of electrical activity were analysed. The components of the MRP in freehand drawing have been described in the part of this research already object of publication (Leandri et al., 2021). They are referred to by their polarity (Positive or Negative) and the time point, in ms, where they peak (with a minus sign - for before trigger and plus sign + for after trigger). The components of interest for this work are N-150, P-40, N+30, P+120, N+300. The amplitudes of peaks were measured with reference to the zero baseline.

3.3.1.6 The EMG recording

The EMG signal was analysed in a time window of 800 ms before to 800 ms after the sensor output signal. Activity of forearm muscles was detected by two surface tab adhesive electrodes (Bionen S.a.s., Firenze, Italy), with the electrodes placed on the forearm, approximately at its middle third. Impedance was kept below 5 KOhm and the electrodes were securely attached to the skin, to minimize movement artefacts. Eye movements were also monitored by two couples of surface tab adhesive electrodes positioned at the outer and inner cantus of the eyes. Signals were amplified 100,000 (EEG) and 10,000 (EMG) times, by analogic amplifiers (LT Bioamplifiers by Vertigo, Genova, Italy) with filters set at 0.1-300 Hz (3 dB points) for the EEG and 10-300 Hz (3 dB points) for the EMG. They were then digitally converted with 1KHz sampling frequency (NI PCIe-6320, X Series Multifunction DAQ, 16 Bit, 250KS/s sampling rate, by National Instruments, Austin, Texas).

3.3.1.7 Signal processing and analysis

Signals from the EEG, EMG electrodes and piezoelectric sensor, plus pen position and status from the tablet were streamed to a LabView 2019 TDMS file© (National Instruments, Austin, Texas) for later analysis with dedicated software The signal from the piezoelectric sensor was rectified and used as a trigger for the EMG and EEG events. Amplitude of this signal was proportional to the pressure exerted when the pen tip touched the tablet surface. In order to ensure that only movements pertaining to a natural light touch were analised, the recordings linked to a sensor signal larger than 0.6 V at its peak were discarded. A detailed description of these events is provided in section 3.3.2.1 and Fig. 3.22.

3.3.1.8 Quantification of the EEG averaged signal

In order to measure the signal amplitude, a mean zero baseline was calculated for each averaged signal epoch; amplitudes of relevant peaks were measured in microvolts with reference to the baseline. As the recorded signal was not periodic, the zero baseline was calculated based on the mean value of all 1600 points constituting the epoch of interest referred to the zero voltage of the analog to digital (AD) conversion board. Once the single averages of all subjects had been calculated, an average of the averages, the *grand average* was computed, in order to provide a clearer idea of the MRP general shapes in the two conditions (Luck, 2014).

Energy related to the recorded signal was calculated by applying the algebraically simplified formula $E(\mathrm{pJ}) = (V^2 t)/R$, where $E(\mathrm{pJ})$ is the energy expressed in pico-Joules (10^{-12} J), V is the voltage value in microvolt of each sampled point, t is the time interval in milliseconds, and R is the electrical resistance across which V is theoretically measured, conventionally considered as equal to 1. In our case, we used two time intervals, the pre-motion between -200ms and T0, and the post-motion, between T0 and 200ms. An explanation of the choice to assess signal energy rather area under curve or power in this case is detailed in section 4.5.

3.3.1.9 Statistics

Descriptive statistics and Student's T test were used where needed, with a p value < 0.01 set as significance level. The Shapiro–Wilk test was used to assess normal distribution of the data when needed.

3.3.2 Results

3.3.2.1 Synchronization of events

In signal averaging it is assumed that the component under investigation is time locked to an external event or to another component acting as a reliable reference, whilst the noise occurs randomly and is cancelled out. Fig3.22 describes a set of preliminary experiments aimed at assessing the reliability of some events candidate to act as a reference. In the order of appearance, the electromyographic (EMG) signal comes first, and its onset could in theory be used as a time reference (Shibasaki and Rothwell, 1999). We studied two conditions of movement. First a strong, very definite tapping, not followed by further movements and resembling the push of a button. The second condition was to imitate the act of drawing, with just a light contact of the pen tip with the tablet, followed by a brief movement of the pen in a drawing stroke. An example of rectified EMG recording in the first condition is shown in the trace b of Fig.3.22. Here a clearcut EMG burst can easily be identified against a background of much lower random activity, obviously due to synchronous recruitment of several motor units to execute the sharp single movement. The onset of such burst is marked by the vertical dotted line 1 . However, in the second condition the EMG shows either a brief and very small burst (trace f of Fig. 3.22) or even no burst at all (trace g of Fig. 3.22) linked to the pen contact and no onset can be identified in the single record. It is important to note that during the complex drawing-like movements a relevant background random EMG activity, occurring as single spikes or short bursts, is recorded, hiding completely or partially the EMG that ought to be used as a reference. It was concluded that given the circumstances in which the movement was taking place, the EMG signal could not be used as a timing reference, though it was worth recording for offline analysis.

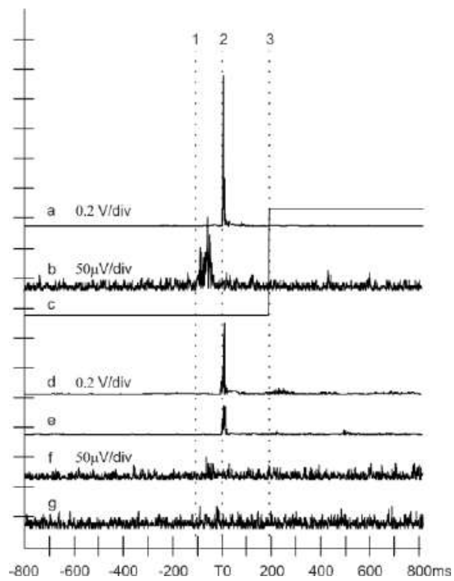

Figure 3.22. This is to show the results of the two preliminary experiments to investigate the timing relationships among the recordable events, without any averaging. Traces a, d and e are recordings of the piezoelectric output. Trace c is the digital USB signal, and b, f and g are the EMG activity. All traces show the recording of a single epoch of the raw analog rectified signal at the output of the amplifiers. Traces a, b and c are obtained after a strong tapping on the tablet surface (condition one), whilst traces d, e, f and g are related to a light tapping (condition two). After strong tapping, an EMG burst is well identifiable and a clearcut time relation between its onset (vertical dotted line 1) can be established with the piezoelectric signal (vertical dotted line 2) and the digital USB signal (vertical dotted line 3). Conversely, after light tapping, no definite reference can be detected in the two samples of EMG recordings (f and g). The piezoelectric signal is smaller than in condition one, signifying that a lesser effort has been used in tapping. T0 is the onset of the piezoelectric signal and the time reference to all traces (From Leandri et al. 2021).

When the pen was held in quiet condition, the piezoelectric sensor only produced a very low background noise, with a root mean square (RMS) value of approximately 0.1 mV. As the pen was moved to start drawing a small deflection peaking approximately between 2 and 10 mV above the zero line could be seen (obviously due to acceleration of the pen sensed by the piezoelectric device), immediately followed by a large, sharp peak when the pen tip touched the tablet surface. The peak onset is marked by the vertical dotted line 2 in Fig. 3.22. The session when the subject was asked to perform an isolated strong tap yielded a signal peak amplitude always above the 0.6 V, reaching up to 1.5 V. On the other hand, peak amplitudes after light drawing–like taps (traces d and e of Fig. 2) were between 0.2 and 0.6 V. Anyway, even in this condition the piezoelectric sensor provided an excellent signal to noise ratio and a very well defined change of state in the time domain. So, it was hypothesized that this event could be used as a trigger reference for EEG and EMG analysis irrespective of the force used to touch the tablet. In order to ascertain the reliability of such choice, the time relationship between the EMG and the piezoelectric peak was examined in the recordings taken in the strong tapping condition, where the single EMG bursts were well visible. An analysis was performed on the 86 epochs where the EMG (trace b) and piezoelectric signal (trace a) could clearly be identified. The interval between the onsets of the two events (vertical dotted line labelled 1 for EMG onset, and 2 for the piezoelectric) had a mean value of 80.6 +/- 10.7 ms and was normally distributed (the Shapiro–Wilk test yielded $W = 0.979$, p-value = 0.176). Such interval included the electromechanical delay (EMD) of the involved muscles and tendons, plus the time for the pen tip to reach the tablet over a distance of few millimeters. Summing up, such interval could be considered fairly constant with a limited jitter. It could be assumed that even in the light touch condition a similar time relationship would exist between the piezoelectric signal and the EMG onset, though the latter could not be seen any more within the single epochs.

The used software could pick up the event "pen down" transmitted by the tablet via the USB interface. Once again, in order to assess the time delays as precisely as possible, we made reference to the strong tapping session (traces a, b, and c in Fig. 3.22). The rising edge of the USB digital signal identified the event (vertical dotted line c), with an obviously large delay after the EMG onset. The delay had normal distribution (W = 0.986, p-value = 0.511) and mean value of 281+/-37 ms. Obviously, the jitter of the USB signal was too large for its use as reference for averaging, and the piezoelectric signal which had a much smaller jitter was eventually chosen.

3.3.2.2 Drawing sessions.

Subjects were required to draw with short strokes, so that the entire picture could be completed with no less than 100 contacts with the tablet surface. Coordinates from the tablet were recorded during the whole session, providing data about length of the stroke and related velocity. The mean length of the stroke was 5.91+/-1.90 mm and mean velocity 8.81+/-3.17 mm/s. A sample EEG and EMG recording from a single subject is shown in Fig.3.23. All traces are raw averages of 125 single epochs where no software filter has been applied, hence the noise due to the background EEG unrelated activity is still well visible. In this and other figures negativity at the non inverting input (active electrode) is upwards The top trace shows the result (at the C4 electrode in this case) from the actual drawing session, where at least five main deflections can be observed to occur before and after the piezoelectric time reference occurring at T0 and marked with the vertical dotted line labelled *'pen down'*. In order to provide a clearer idea of the response components and to assess their occurrence across subjects, a grand average was performed after a further software filtering with a lowpass frequency set at 30 Hz. This procedure cleaned the responses from the high frequency noise so the single components could be better identified and quantified. The top set of traces in Fig.3.24 shows the grand average in bold, and the nine individual averages as greyed lines, obtained after the drawing session. The recorded components were classified as PreT0 or PostT0 relative to their occurrence before or after that time and preceded by the – (minus) or + (plus) sign accordingly. Table 1 summarises latency and amplitude of the five most relevant components, which were named after their peak polarity and average latency: N-150, P-40, N+30, P+120, N+300. Amplitudes were referred to the baseline. The most relevant feature in drawing sessions was the set consisting of N-150, P-40 and N+30. These peaks were very consistently recordable in all subjects with comparatively high amplitude and little jitter in their latency.

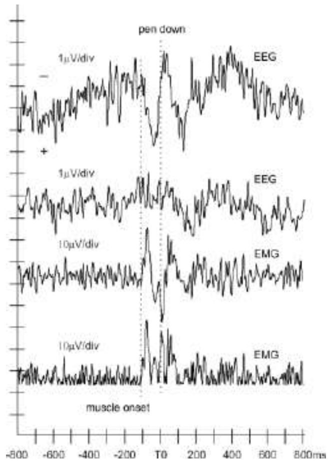

Figure 3.23. Averages of 125 epochs from the EEG and EMG unfiltered channels in one subject related to the salient drawing movement (top trace), or to simple light tapping (second trace from top). Temporal reference is the pen down event detected by the piezoelectric signal and marked by the vertical dotted line at T0. The same averaging process and same temporal reference have been used to process the EMG signal in order to extract the EMG burst related to the relevant movements and otherwise hidden by the background noise. No difference had been found in the averaged EMGs between drawing and tapping sessions, so just one set of EMG events is shown here. In the third trace from top is the unrectified EMG, and in the fourth trace is the rectified recording. Only in these averaged traces is possible to detect the onset of the burst, either rectified or not (From Leandri et al. 2021).

Latency in ms referred to T0						
		N-150	P-40	N+30	P+120	N+300
Drawing	Mean	-147.9	-42.6	31.3	120.4	310.3
	Sd	*17.0*	*4.7*	*13.4*	*17.1*	*19.5*
Tap	Mean	-154.5	-59.0	41.6	130.2	308.0
	Sd	*33.6*	*24.9*	*29.3*	*29.3*	*40.8*
Amplitude in mV, peak value referred to baseline						
Drawing	Mean	1.03	**2.28**	1.69	1.16	1.42
	Sd	*0.49*	*0.5*	*0.97*	*0.6*	*0.62*
Tap	Mean	0.82	**0.43**	1.00	1.57	1.25
	Sd	*0.21*	*0.45*	*0.29*	*0.72*	*0.56*

Table 3.1. Latency and amplitude of components. Figures in bold are very significantly different

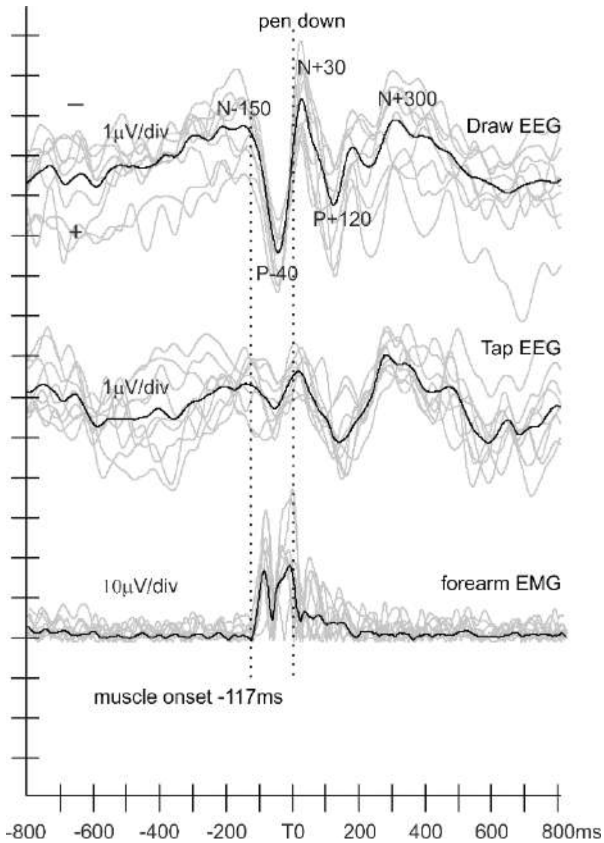

Figure 3.24. Averages of the 9 subjects as greyed traces and grand average in bold. The high frequency noise, visible in Fig. 3, has been filtered out by software in the EEG and EMG traces. The pen tip touched the tablet surface at T0; the event is also labelled as "pen down" and marked as a vertical line on the three sets. Top set: recordings from the drawing sessions show in all subjects a very clear triphasic component (N-150, P-40, N+30) occurring immediately before and after the pen down event. The first negative peak (N-150) takes place just before the onset of muscle depolarization (bottom set). Middle set: during the tap session a meaningless gesture was performed which gave rise to much more variable responses where the same components can be observed, but amplitude and energy of the pre-T0 epoch are much smaller than in the drawing session. Bottom set: averages from forearm muscles improve the signal to noise ratio and provide a good detection of the rectified EMG burst, whose onset occurs almost simultaneous as the N-150 component of the EEG. The largest EEG potentials (P-40) occurred during muscle activation. All latencies are referred to T0 (the pen down event detected by the piezoelectric sensor) (From Leandri et al. 2021).

3.3.2.3 Tap sessions

Alternate with drawing, subjects performed as many sham sessions mimicking the same gesture as during drawing, but with no other specific end. They simply had to lightly tap the pen approximately every 2 seconds on the tablet and shift the pen point for the average length of the strokes used while drawing. Data collected from the tablet interface showed that the pen had been shifted for a mean distance of 6.04+/- 2.54 mm and with a speed of 9.96+/-2.54 mm/s. So, extent and speed of movement were similar to the act of drawing, the only difference being absence of saliency. The scalp recorded activity is reported unfiltered in Fig2.23, second trace from top for a single subject, and after software filtering in Fig. 3.24 (second set from top) where the single averages are represented as greyed lines and the grand average in bold. A simple visual inspection of the traces shows that these were much more variable in shape than during the drawing sessions and that the waveshapes of the PreT0 epoch were much less noticeable. Mean values of amplitude and latency of components from the tap sessions are summarized in table 3.1. The grand average identified similar peaks as in drawing, but the largest of them, P-40, was subject to a dramatic decrease in amplitude. There was a mean difference of 1.84 μV (p=5.5E-07) with a drop of 81% from its former value. Those peaks occurring after the T0 time showed no significant differences with the drawing session. As to the latencies, although no statistically significant difference could be found between drawing and tap sessions, it is worth noting that standard deviations were much higher in the tap sessions, suggesting a much higher variability of the signal.

3.3.2.4 Signal energy

Measurement of peak amplitude can only provide one part of information related to the underlying amount of neural activity, whilst energy of the recorded signal may be considered a more suitable and comprehensive reflection (Leandri et al., 2008). Computation of signal energy in the time epoch between -200 ms and T0, provided a mean value of 325.9 +/- 133.8 pJ in drawing sessions, compared to just 55.57+/- 24.48 pJ in tap sessions. There was then a remarkable difference of 270.33 pJ (p=2E-05), with a decrease of 83% from the previous value. No significant difference between the two sessions was found when energy was calculated for the T0 to 200ms time epoch.

3.3.2.5 Comparison between EEG and EMG signal

Electromyographic activity was recorded alongside the scalp response, but, as said before, not used as a trigger because of the unfavourable signal to noise ratio involved in the explored movements. Though the EMG burst could not be seen in the single epochs, it was possible to detect it after a process of back averaging using for a trigger reference the piezoelectric signal, likewise it had already been done with the EEG. In Fig 3.23 the raw back averaged EMG of a single subject is shown in the third trace from top, and the average of the rectified same signal is shown in the fourth trace. In Fig. 3.24, third set from top, the same rectified and filtered signals from all subjects are shown as greyed traces, with their grand average in bold. Initially, EMG traces were separately averaged during the drawing and tapping sessions, but as there were no statistically significant differences between their latencies and amplitudes, and their waveforms were very similar, later on they were averaged irrespective of the session. The recording of the EMG activity was performed in order to better understand the timing of neural events and to compare these new results to those already published by the authors who used the EMG as trigger signal. The mean onset of the nine averaged EMG traces occurred at the latency of -117+/- 8.0 ms, before the piezoelectric trigger. A comparison of the EMG onset with the EEG N-140 recorded during the drawing sessions is legitimate because the same piezoelectric trigger was used for both. The time difference between the two events was 30.6 ms, statistically highly significant (p=1.6E-3) and compatible with a motor cortex to muscle transmission time.

3.3.3 Discussion

3.3.3.1 Dealing with drawing movements

No previous examples to movement related potentials using digital drawing tablets have been found in the literature. Movements during drawing are extremely complex and there is little hope to succeed in examining them without encumbering the subject with a large number of electrodes and leads to monitor the activity of as many muscles. Such setting would greatly limit the gesture extent and liberty, still risking to lack completeness in faithful detecting the very first occurrence of motion. Since the present aim was not mapping muscle activity, but finding the link between cortical activity and gesture, it was deemed that monitoring the gesture itself would be a more straightforward and simple method. This is today possible by means of drawing tablets and related pens, which are sensitive not only to the simple touching of the drawing surface and its coordinates, but to subtle details like pressure and tilt.

3.3.3.2 Synchronizing the gesture

Most of the movement related research has been performed taking as trigger, or point zero, the onset of the EMG burst of the muscles involved in the movement. This is an apparently precise reference, but it is not devoid of uncertainties due to i) difficulty in identifying the correct muscle that will be activated as the first one to execute the movement; ii) once that muscle has been identified, the movement must always be the same, to avoid recruiting other muscles first; iii) the burst onset may suffer a jitter according to the strength and speed of movement; iv) sometimes the main EMG burst that is accompanied by the mechanical effect may be preceded by a short, possibly mechanically ineffective electrical activity; which one of the two onsets should be considered? Such drawbacks are present in an ideal situation when the EEG is studied in relation to movements separated by moments of rest with very little residual muscular activity. This sort of movement has been used for the preliminary experiments described in section 3.3.2.1 and depicted in Fig. 3.22, traces a and b. In the case of natural, continuous and complex movements performed in drawing, the recorded EMG activity could not possibly identify the very small, light movement of gently touching the tablet. As demonstrated in traces f and g such activity is not to be seen in single epochs, and only a back averaging triggered by the tip touching the tablet can detect such hidden activity. Of course, the use of a mechanical sensor implies a delay with respect to the electric depolarization of motor nerve or muscle fibres, usually called the electromechanical delay. To which, in our case, we have to add the time of the pen tip to be displaced for few millimeters.

However, if such delay is maintained reasonably constant by a monitored effort (only the epochs when a limited strain was applied to the sensor were considered, as in traces d and e of Fig. 3.22) it may be assumed that the mechanical event could be used as a trigger for the EEG and EMG events, both for back and forward averaging. In case of excessive variability of the averaging reference, no reliable components would be identified because the peaks of interest would fall into the category of pseudo-random variables (Campbell and Leandri, 2020; Collura, 1995). The fact that a definite set of components can be recorded on the EEG is an empirical demonstration that the chosen trigger is reliable enough. In section 3.3.2.1 the results about the USB timing have been reported, with the conclusion that the jitter of the serial transmission of data was far too large, so the hypothesis of using the USB digital signal as trigger was discarded. Solutions to this drawback are possible via hardware and software (Lim et al., 2017), but regretfully none of them could be implemented at short notice, so it was decided to resort to the piezoelectric sensor fitted to the pen tip in order to detect the touch of the tablet surface. Obviously, in the act of drawing after the first contact, the sensor was subject to further minor strains and continued to deliver a weak electric signal, that is visible in the traces d and e of Fig. 3.22 after T0 time. The presence of the sensor did not impair the smoothness in drawing, as attrition with the glossy surface of the tablet was minimal. One added value of the piezoelectric sensor was the possibility of monitoring the force of contact so that a window could be established to rule out contacts too strong, that could have been the source of increased amplitude of the movement related potential in lieu of the genuine saliency effect, as force is a recognised causative factor (Shibasaki and Hallett, 2006). All subjects were asked to draw in short strokes, so to collect the required amount of epochs for averaging in a reasonable amount of time by using a rhythm of approximately one stroke every two seconds, which was the observed usual rythm during quiet easy drawing.

3.3.3.3 Saliency of the gesture

One important difference between the present experiment and past research is the extent and force of movement. Whilst previous experiments had implicated mechanically relevant actions, in the present case the pen was held in a standby position just a few millimeters above the tablet surface; a simple relaxing of hand extensor muscles could achieve the required drop. Even the amount of muscle work for the subsequent stroke was very limited, so it was expected that any EEG reflection of muscle strength employed in the gesture could hardly be detectable in such conditions. It is known that complex tasks are correlated with larger cortical potentials and that imagined movements could give rise to EEG activity in absence of mechanical dislodgment (Shibasaki, 2012); on such grounds it was hypothesized that providing a task for drawing would yield different and possibly larger cortical potentials compared to a similar but not salient activity. Subjects, who were experienced in drawing, were asked to trace over a photograph of some complexity, and we chose a reproduction of hands for such aim. Although tracing over a picture may seem an easy task, it takes some ability and experience to reproduce masses and tones of the original image with a simple outline to obtain a similar perception in the onlooker. Actually, it is a rather demanding task, and the subjects had to draw with attention, forethought and excellent control of the hand. Short strokes also meant that connections between successive drawn lines had to be tight so as to render the outline as a single uninterrupted line. Contrary to the drawing-tracing task, the simple tap and meaningless line tracing offered no need of forethought or ability, possibly involving much scanter cortical activity which could be reflected into smaller or somehow different scalp recorded potentials.

3.3.3.4 Scalp recordings

This study was designed to demonstrate that EEG movement related potentials could be detected in a sort of steady state modality, not dissimilar from the description provided by Gerloff et al. (Gerloff et al., 1997). Based upon such information some preliminary recordings were performed to ascertain which derivation could best provide a reasonable compromise between the amplitude or pre- and post-motion responses, so that both of them could be recorded. It turned out that C3 in right handed subjects was a correct location (C4 in lefthanded), referred to the ipsilateral mastoid. The complex N-150, P-40 and N30 was in all subjects the largest recordable component and was strongly linked to the complexity of the task in drawing sessions. Its amplitude dropped dramatically in the tap sessions, thus providing a completely different shape to the general waveform. The largest peak of the complex, P-40 is to be compared to the pre-movement potential+50 described by Gerloff et al. (Gerloff et al., 1997) as the "positive parietal deflection" which "starts at approximately 50 ms after the EMG onset". Making reference to the onset of the EMG recordings it is easy to calculate that P-40 occurs 73ms after it, a figure not far from the value given by the Gerloff et al.. Strictly speaking, the P-40 is not a pre-motion potential as it occurs after the onset of EMG activity. From this point of view it should be considered a in-motion potential, because it takes place in the time epoch of the averaged EMG burst. An interval of approximately 37 ms and compatible with a cortex to muscle transmission time, can be calculated between the cortical N-150 and the EMG onset. The EMG activity showed no significant difference between drawing and light tapping sessions, whilst EEG potentials did. This finding suggests that cortical activity was much higher in case of drawing, while the work of the final effector, the muscle, was just the same.

3.3.3.5 Assessment of cortical activity as area under curve and signal energy

Measurement of the area under curve is considered a more sensitive parameter than the peak amplitude in neurographic and evoked potential studies (Jorge et al., 2019; Stålberg et al., 2019). It is calculated as the integral of the signal amplitude over a definite period of time, and expressed in "V.s" units. Since the whole area comprises both positive and negative deflections, the calculation is performed after rectification. However, since we are using an electric signal, it looks more appropriate, from a physics standpoint, to calculate energy (expressed in Joules) of the signal by squaring the amplitude and multiplying it by the time (Duarte, 2013). It is worth remarking that whilst energy is a measure of the cumulative strength of an impulsive signal (like the events occurring in an evoked potential) referred to a finite time (in our case we measured the signal energy in the time interval between -200 and +200 ms from T0) , power, measured in Watts is the instantaneous strength of a continuous signal (like a streaming recording of EEG, not our case), and is referred to a signal of infinite (or very long) duration (Duarte, 2013). By using area under curve or, more appropriately, energy assessment, it is possible to include the electrical activity not only of the excitable tissue occurring at the peak latency, but also all activity preceding and following it, within the time boundaries set for calculation. This is due to a much larger group of fibres or neurons, which, of course, do not depolarize simultaneously. It may be regarded as a more trustworthy way of quantifying the neural activity (Leandri et al., 2008). As we reported, even such measurement shows a very relevant and significant difference between drawing and tap sessions, confirming the amplitude differences.

3.3.3.6 Differences in movement related potentials between drawing and tap sessions

Both in drawing and tap sessions pre-motion activity starts earlier with a slow increase, but it has similar amplitude and energy until the N-150, where the big difference starts to show. After P30, in the post-motion epoch, the difference again returns not significant. May be that in a larger population sample or in other conditions, some differences even after movement could be significantly detected. However in the present data the big difference is just at the beginning of muscle depolarization and during it, although the muscle activity itself is unchanged. It looks like the task difficulty gave rise to a higher cortical activity just very shortly before and after sending commands to the muscles. The finding of enhanced cortical potentials just before a meaningful movement, independent from the amount of muscle involved, is in accordance with previous findings (Kitamura et al., 1993). Compared to traditional studies in movement related potentials, where motor activity was not repetitive or much slower, we detected changes due to saliency of the gesture which were of shorter time duration, but perhaps more remarkable as to their amplitude. Such differences could be due to dissimilarity in cortical function between ahead planned movements and fast repetitive but salient ones, where rapid decisions had to be taken.

3.3.3.7 Limitations of the study

This study represents the first attempt to study the EEG movement related potentials during free natural drawing and was meant to be a feasibility study, whose first encouraging results prompted to complete the successful experiments though with a limited number of subjects. Obviously only nine subjects are enough to validate the method, but not sufficient for a comprehensive physiological study. This is an important limitation, that can be overcome in the near future. Another limitation is the just one scalp derivation used to record the EEG activity. This was done on purpose, with the aim to avoid encumbrance to the subject, who should be free to draw as naturally as possible. Studies on scalp distribution of movement related potentials had been performed by many authors and it was felt that there was no immediate need of replicas. The choice of the reference electrode on the mastoid ipsilateral to the scalp electrode could be considered non optimal, as the contralateral mastoid could have been a more neutral point. Lastly, the synchronization reference for back averaging is not optimal because of jitter occurrence, but, provided that the statistical distribution of jitter is normal, then a large enough sampling should provide a reliable reference value. On the other hand, the very spirit of this research is to correlate the result of complex movements to the EEG activity, and no other choice was compatible to our set rules of "ecology".

3.3.3.8 Conclusion

This experiment demonstrated that it is possible to use a simple 'ecological' method, based upon a low cost drawing tablet, to record movement related cortical potentials during freehand drawing without constraints to the investigated subject. It was shown to be a valid tool to detect very relevant differences between motivated and unmotivated drawing movements. The main components of the time periods before and after movement have been individuated; their parameters and reliability assessed. This method can now be used as the basis for further experiments involving different types of drawing tasks.

3.4 Experiment 2. Movement Related Potentials during freehand drawing and CAD-like designing

The second set of experiments was aimed at assessing differences in the recorded MRPs during freehand drawing on a digital drawing tablet compared to designing with mouse and vectorial software, at imitation of CAD. The subjects were asked to perform two tasks; the first one was identical to the meaningful freehand drawing of the Experiment 1, but the second one, instead of a simple tap as in Experiment 1 required to insert coordinates in vectorial graphics with a mouse, hence the attention required was definitely higher. Still, it was hypothesized that the freehand drawing would be much more cognitively demanding than the use of the mouse.

3.4.1 Materials and methods

3.4.1.1 Subjects

Twenty healthy subjects volunteered to take part in the experimental sessions. Their age ranged from 24 to 46 years, 16 of them were females and 4 males. All of them were right handed, had experience in freehand drawing with digital tablets and in computer aided design (CAD) with a mouse. Before the real recording session, they were asked to take part in some introductory sessions to become familiar with the research tasks including getting practice in handling the modified pen and mouse (see section 2.3). This research has been carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans and all subjects provided informed consent to the procedure and to handling of data, which were anonymised.

3.4.1.2 Tasks to accomplish

Each subject was asked to perform two simple tasks in two separate but consecutive sessions. The first one was to trace over a half-bust portrait shown on screen by free hand drawing with a pen, digital tablet and raster graphic software. The subject was free to choose which parts of the portrait to trace over provided that a resemblance between the tracing and the original figure was eventually detectable.

The second one was to trace over a photo of the front of a building. This simulated a simple architectural computer aided design (CAD) drawing with mouse and vector graphic software using straight lines. The vector graphics application was much simpler than a true CAD software letting the subject to concentrate on drawing the lines, and avoiding unnecessary movement to search across menus. In the freehand session the subjects were asked to draw by keeping the pen hovering on the tablet surface, then touching the tablet and starting a short stroke of about 20-30 mm, and then lifting the pen about 2 mm. The time interval between two consecutive movements should be approximately 2 s. In order to analyse the MRPs (see next section 3.4.1.3), it was necessary to record 200/300 movements performed in the same session for each subject, which took approximately 10-15 minutes. To use the mouse, each move started with a left click, and should have a similar length as the freehand used pen. In Figure 1 are depicted the two figures that had to be traced over with pen and mouse, with some sample tracings in bold, just as it would appear on the screen.

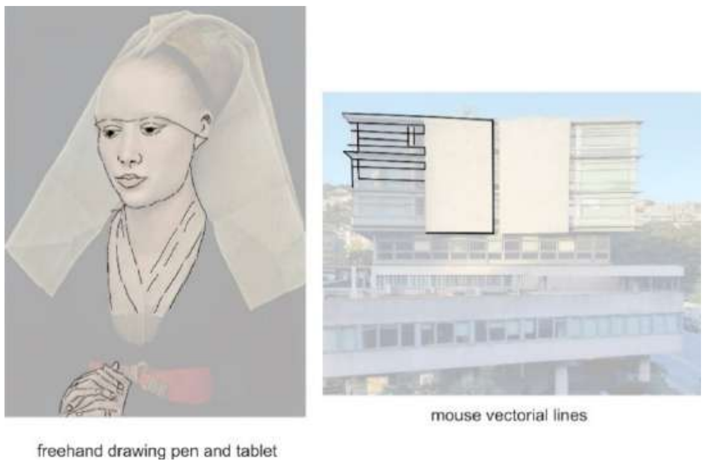

Figure. 3.25. The first drawing task involved tracing over the photo on the left in freehand style with pen and tablet. Shadowing was permitted. For the second task, subjects had to trace straight lines over the photograph on the right, using mouse and a vectorial software package. Both images were presented in a layer with opacity set at 40%. The portrait is ‘Portrait of a Dame’ by Rogier van der Weyden, Andrew W. Mellon Collection, National Gallery of Art, Washington. The building photograph is by the author.

3.4.1.3 Equipment and data recording

This research did not aim to map the EEG over the scalp, so a single derivation was used, adopting the one already used in the first experiment (Leandri et al., 2021). This had the advantage of not having multiple wires from electrodes which would have interfered with freehand and mouse movements. The active electrode was placed over the cortical representation of the hand on the contralateral hemisphere (C3 of the 10-20 EEG system); the reference electrode was on the mastoid on the same side. A negative-going signal at the active electrode is shown as an upward deflection in all our graphs, according to the neurophysiological convention. The signal was amplified with a gain of 50000 and bandpass of 0.1-2000 Hz (2^{nd} order Butterworth filter, LT biological amplifiers by Vertigo, Genova, Italy), sampled with dwell time of 1 ms with an analog to digital (AD) converter board (NI PCIe-6320, X Series Multifunction DAQ by National Instruments, Austin, Texas) and streamed to a hard disc using dedicated software written in the LabView 2019© language (National Instruments, Austin, Texas).

Additional recording sessions were performed with 6 of the subjects in which activity of forearm muscles was simultaneously recorded by placing two electrodes on the skin surface at the proximal third segment of the forearm. The aim of these electromyographic recordings was mainly to make approximate comparisons between the amount of work expended for freehand strokes and for mouse moves. This technique suffered from the limitation that the electrodes had to be wired to the same limb used for these movements, therefore hampering its freedom. For this reason, the simultaneous recording of EEG and EMG was only performed in a limited sample. The EMG was amplified 10000 times, with bandpass of 5-2000 Hz, and streamed alongside the EEG as a separate channel onto the same file. EMG activity of the orbicularis oculi muscle was also monitored to discard contaminated EEG recordings in the off-line analysis.

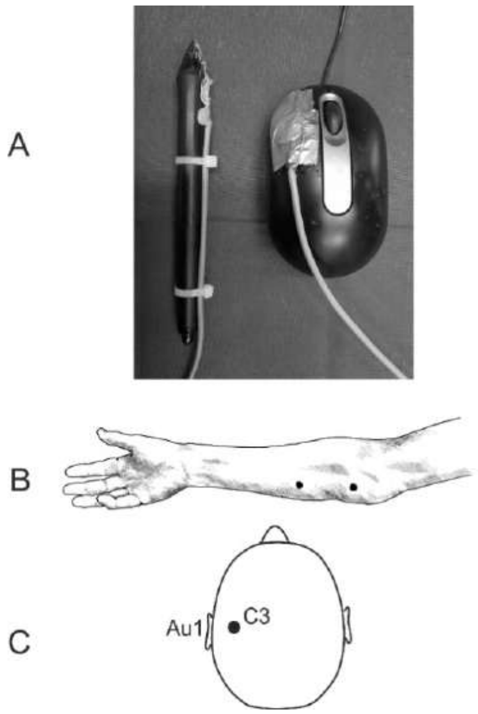

Fig. 3.26. Recording setting. In A the modified pen and mouse with attached the piezoelectric sensor are shown. B shows the placement of electrodes to record activity of flexor forearm muscles. C shows the scalp electrodes for EEG recordings. Image by the author.

The freehand drawing equipment was an Intuos© PTK-640 tablet (Wacom Co. Ltd., Saitama, Japan) with a Wacom KP-501E-01 pen, which had been modified by adding a piezoelectric sensor according to the specifications already provided (Leandri et al., 2021). The sensor was used to detect when the pen tip touched the tablet surface and the drawing movement started. Because the sensor was placed asymmetrically and the pen was slightly tilted during the drawing stroke, it was not activated by further pen movements during the stroke. The signal from the sensor was recorded simultaneously with the EEG and provided the necessary trigger signal. A similar device was attached to the mouse, so that each time that the left button was pressed, a signal would be produced. Figure 3.26 shows the modified pen and mouse, and the setting of recording electrodes on the scalp and on the forearm muscles. The distance and related speed covered by the pen tip after the pen down event and by the mouse after each click were monitored by using dedicated LabView® functions, after converting metric units (mm) into screen pixels for each of the two devices.

3.4.1.4 EEG signal analysis

The EEG was recorded with the same settings as in Experiment 1, where the usual components of interest for this work are N-150, P-40, N+30, P+120, N+300 should be recognisable. The amplitudes of peaks were measured with reference to the zero baseline. In this experiment, we also calculated the *area under curve* rather than *energy* because the software to calculate the former was temporarily unavailable. The area was computed as the integral of the signal amplitude for the time windows going from -500 ms (before trigger) to 0 (time of trigger) , and from 0 to +500 ms (after trigger). In this case it was expressed in μV.ms units (see Figure 3.29) as a graphical example of area calculation and zero baseline). The zero baseline was calculated based on the mean value of all 1600 points constituting the epoch of interest referred to the zero voltage of the analog to digital (AD) conversion board. Once the single averages of all subjects had been calculated, an average of the averages, the "grand average" was computed, in order to provide a clearer idea of the MRP general shapes in the two conditions (Luck, 2014).

3.4.1.5 EMG signal analysis

The EMG signal was analysed in a time window of 800 ms before to 800 ms after the sensor output signal. In order to compare the muscle activity involved in freehand versus mouse drawing, we performed a grand average of rectified EMG recorded in 20 time epochs for each of the two conditions. The area under curve was then calculated.

3.4.1.6 Statistical analysis

Data were summarised using descriptive statistics. The characteristics of the averaged signals produced by pen and mouse drawings were compared using independent groups t-tests. Statistical significance was accepted at the 5% level ($p<0.05$).

3.4.2 Results

3.4.2.1 EEG averaging and filtering in freehand drawing with pen and tablet

As predicted, the movement of a single stroke of the pen produced no visible or consistent event on the EEG recording. The upper part of Figure 3 shows five EEG traces each generated by a single stroke, but there is no detectable deflection related to the trigger signal (which is represented at the time marked as T0 on the x axis of the graph). However, when the averaging method was applied to the EEG recordings from 200 strokes, a dramatic increase in signal to noise ratio took place, and a clear waveform could be delineated (sixth and seventh trace). The addition of low pass filtering further reduced the high frequency noise components and the peaks N-150, P-40, N+30, P+120 and N+300 already described by Leandri et al. (Leandri et al., 2021) could be identified.

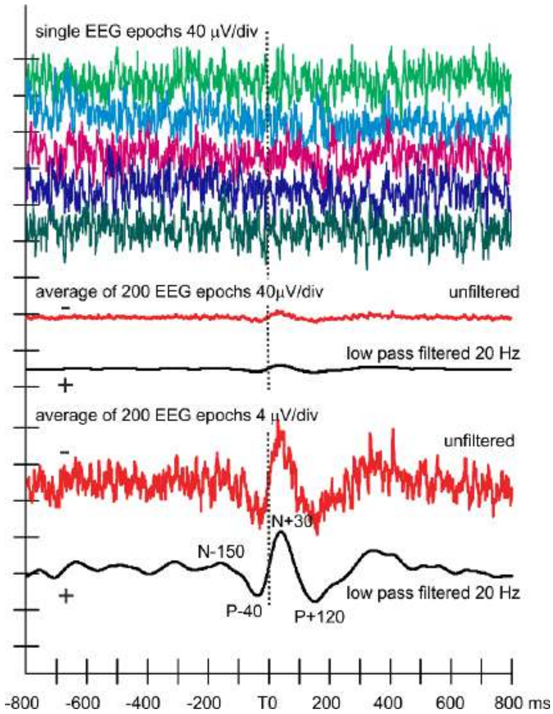

Figure 3.27. EEG recording from a subject. This shows that in single recordings no waveform pattern was recognisable in relation to the hand movement detected by the pen sensor (first 5 traces from top) and marked here by the vertical dots in line with T0. After averaging 200 such recordings, the noise was considerably reduced and some very small peaks could be observed before and after the hand movement (sixth trace, in red). High frequency noise still interfered with the MRP signal, so a digital low pass filter of 20 Hz was applied, producing the trace in black (seventh trace from top). The bottom two traces are the result of a ten time amplification of traces six and seven, to show how much the high frequency noise still impeded correct recognition and quantification of smaller peaks (red trace). They are made better visible in the bottom black trace by a low pass filter. Image by the author.

3.4.2.2 Analysis of the task-related averages

The upper set of traces in Figure 4 shows a superimposition of the MRPs from every subject recorded during freehand drawing, where the waveforms were reasonably similar each other. The lower set reports MRPs recorded when subjects used the mouse to draw vectorial straight lines. Table 1 reports the mean values of each peak calculated across the 20 subjects and compares their time occurrence (latency) and peak to peak amplitudes related to the two tasks.

Freehand drawing with pen and tablet									
	N-150	P-40	N+30	P+120	N+300	N-150 P-40	P-40 N+30	N+30 P+120	P+120 N+300
Measure unit	ms	ms	Ms	Ms	ms	mV	mV	mV	mV
Mean	-142.40	-45.05	27.60	114.25	310.90	1.38*	1.74*	2.52	2.23
Sd	34.05	13.36	10.45	32.78	41.66	1.15	1.31	1.62	1.16
Mouse vectorial drawing									
Mean	-135.55	-52.45	26.95	113.00	289.90	0.66*	0.82*	2.15	2.52
Sd	43.68	27.08	13.07	29.07	69.42	0.29	0.50	0.80	0.92
P	0.583	0.280	0.863	0.899	0.253	0.009	0.005	0.368	0.385

Table 3.2. Latencies and amplitude of peaks recorded during each task. The first 5 columns report mean latencies in ms of identified peaks. Values of peaks occurring before T0 are preceded by a negative sign. The last four columns report mean peak to peak amplitude measurement in microvolts. The last row reports the p value from a Student's t test which compared the values of each measure between the pen and mouse drawing methods. Asterisks mark statistically significantly differences ($p<0.05$) between means.

The traces obtained during freehand drawing differ remarkably from those during mouse drawing, mainly due to reduction in amplitude of the whole trace that occurs before T0 in the case of mouse drawing (Figures 4 and 5). As can be seen in Table 1, there are statistically significant differences in the amplitudes of the peak pairs N-150/P-40 and P-40/N+30 between the two drawing methods. Another method that can be used to interpret the traces and to detect their differences is to measure the area under the curve of the signal component of interest. Table 2 reports the calculated areas in the windows -500/T0 ms and T0/+500 ms. In the case of mouse drawing the area of the pre T0 window was just 41% of that with pen freehand drawing. A smaller reduction was found in the post T0 window with the mouse area being 72% of the pen drawing area.

Freehand drawing with pen and tablet		
	Pre T0	Post T0
mean	394.28*	465.61*
sd	195.14	125.90
Mouse vectorial drawing		
mean	162.10*	333.06*
Sd	57.14	139.80
P	<0.001	0.003

Table 3.3. Areas under curve in the two regions of interest of MRPs; units are mV.ms. P is the value produced by Student's t tests which compared the areas under each curve produced by pen and mouse drawing. Asterisks indicate statistically significant differences (p<0.05)

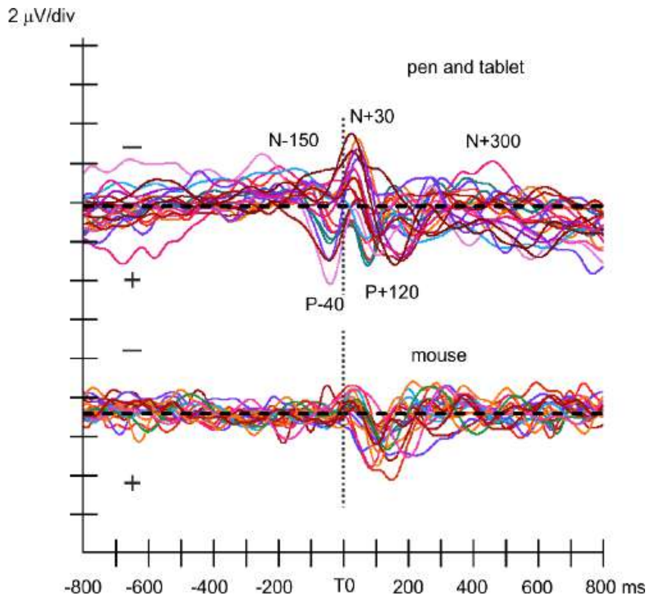

Figure 3.28. MRPs of all the 20 subjects. The top set shows recordings related to pen and tablet freehand drawing. The MRPs components are recognizable in all subjects and are labelled according to the nomenclature previously proposed (Leandri et al., 2021). The bottom set shows recordings after mouse vectorial drawing, where the single components before T0 are often difficult to detect. In both sets the zero baseline is marked by the horizontal dashed line. The vertical dotted line marks T0, the pen down or mouse click event. Image by the author.

3.4.2.3 Grand average

Unavoidable differences in biological function and in the noise components resulted in variation in the averaged recordings between subjects, although within reasonable limits. This variability can clearly be seen in the traces of Figure 3.28. In order to detect a waveform pattern typical of each condition (freehand versus mouse) we performed a grand average of the recordings for all subjects. This is shown in Figure 5. A visual inspection clearly shows the difference between the two conditions, particularly for the pre T0 window. The two drawing methods produce more similar patterns after T0, where the same peaks can be detected, although with slightly smaller amplitude in the mouse drawing.

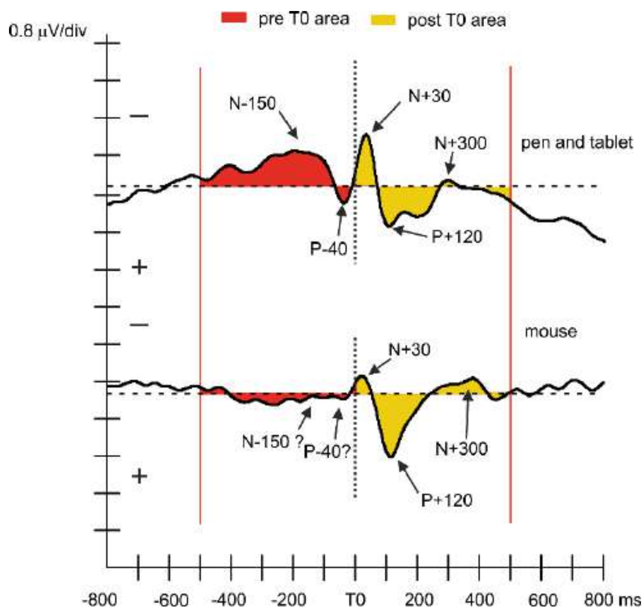

Figure 3.29. Grand averages of single MRPs obtained in 20 subjects during the freehand pen drawing (top set) and mouse vectorial drawing (bottom set). The red and yellow colours mark the areas between the curve and the baseline (shaded horizontal line) before and after T0. The vertical dotted line marks T0, the pen down or mouse click event. The two red vertical lines mark the time boundaries of the areas of interest: 500 ms before and after T0. Top trace: all peaks were identified and labelled according to previous nomenclature (Leandri et al., 2021). Before T0 there is a slow negativity peaking at N-150. After T0 there is a set of waves of alternate polarity. Bottom trace: homologous peaks to the top trace are arrowed and labelled. It is easy to observe that the pre T0 part of the response is shifted downwards and the N-150 and P-40 are difficult to identify, to the point that the N-150 and P-40 are indicated by a question mark. Image by the author.

3.4.2.4 Extent of movement and muscle activity

Assessments of movement extent, speed and EMG of the main involved muscles were deemed necessary to perform a fair comparison between MRPs related to freehand or mouse drawing. The monitoring was performed on the same six subjects that underwent recording of forearm muscle activity. The mean distance covered with each drawing stroke with the pen was 35.57 mm (sd = 27.86), and its mean speed was 35.17 mm/s (sd = 15.01). The mouse data were 48.84 mm (sd=27.40) as to the mean covered distance, and 34.64 m/s (sd= 20.33) for mean speed. It may be concluded that although the two drawing styles were different, the hand performed most movements with similar speed, though the covered distance was slightly longer with mouse than pen. Electromyographic activity of the flexor muscles was recorded in six subjects. The signal to noise ratio was much larger that in the case of the EEG because of the nature of the source, but it was still necessary to perform an average of approximately 20 recordings in order to detect the onset of the EMG activity and calculate its area under the curve. The results are shown in Fig. 3.30.

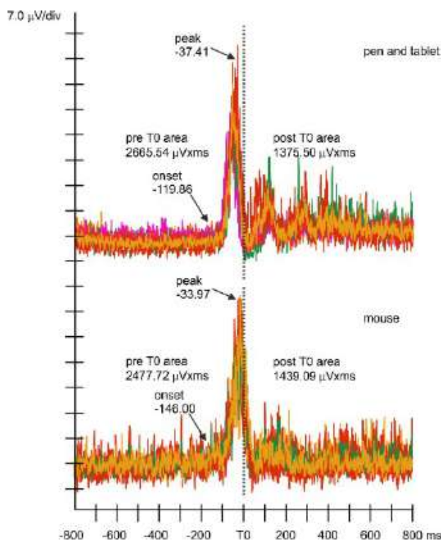

Figure 3.30. Two sets of six superimposed traces of rectified and averaged (20 epochs) recordings from forearm flexor muscles in six subjects, to show that their activity was similar when using pen or mouse. The dotted line marks the piezoelectric trigger signal. Onsets and peaks of the burst linked to the starting movement are marked by an arrow and their mean latencies in ms are reported. No statistical difference is detectable at onset and burst peak, suggesting that the muscle effort occurs at similar times. Image by the author.

The onset of muscle activity before T0 had a mean value of -121.50 ms (sd =13.54) in the case of freehand drawing and of -135.50 ms (sd= 30.23) in the case of mouse. The small difference was not statistically significant. We also calculated the mean value of EMG peak latencies, which were -37.32 ms (sd= 3.72) for the pen and -34.83 ms (sd= 7.01) for mouse, with no statistically significant difference either. These results meant that the first muscle contraction started approximately 130 ms before pen drop or mouse click, and that most of the muscle activity needed for the effective mechanical movement (represented by the peak of the burst) occurred approximately 35 ms before the two pen and mouse events, within the same time span. The area under curve of the EMG was calculated in the same epoch as the EEG, from 500 ms before to 500 ms after T0. In the case of freehand drawing, the mean area before T0 was 2683.61 mV.ms (sd= 628.22), and that after T0 was 1406.37 mV.ms (sd= 473.02). Calculations of the mouse related areas were 2481.56 mV.ms (sd= 281.15) before T0 and 1467.01 mV. ms (sd= 232.94) after T0. The figures for pen and mouse drawing were therefore very similar each other. It could be concluded that the EMG activity, which approximates muscle work, was not different for the two tasks.

3.4.3 Discussion

3.4.3.1 Timing of brain events

The piezoelectric sensors placed on the pen tip and over the left mouse button detected the moment that the pen tip touched the tablet surface or the mouse was clicked, and sent a trigger signal to the AD board as a timing reference for later analysis of the EEG; the reference is marked as T0 in the horizontal axis of the graphs. However, there were a number of delays between the first motor neural activity and the triggering events that should be taken into account. The first part of delay is purely biological and consists of conduction time along the motor pathway to the motor plate of the muscle, depolarization of the muscle membrane, contraction of myofibrils, mechanical transmission of force to tendons and finally to bone segments. The second part of the delay consists of the time needed to move the pen for few millimeters from the hovering position to the surface of the tablet, or to push the mouse button. Such delays are not negligible and can be inferred by using the onset time of the EMG as it is shown in Figure 6. If we take the case of freehand drawing, where EEG events are best identifiable, N-150 occurs approximately 50 ms before the first muscle depolarization. Conduction time between motor cortex and biceps brachii has been estimated in young adults to have an approximate mean value of 13-15 ms (Furby et al., 1992). An educated guess could put the time to forearm flexors around 18 ms. So the N-150 would be perfectly compatible with cortical activity occurring approximately 30 ms before the descending volley. The occurrence of the N-150 peak at about 50 ms before the EMG onset is in accordance with the only one study on steady state fast repetitive movements, where the negative pre movement peak was detected at 57+/-21 ms before EMG onset (Gerloff et al., 1997). Taking the EMG onset as a reference, it is evident that P-40 and all the following EEG peaks occur after muscle activation, so they fall in the range of "reafferent potentials" which are thought to be a reflection of incoming feedback to the sensory and motor cortex (Kornhuber and Deecke, 1965b). In our case, however, the triggering event T0 just marked the beginning of a long lasting movement (the stroke in the freehand drawing and the mouse drawn line in CAD), so it is likely that a summation of motor and sensory neuronal activity contribute to the EEG recordings in the post T0 epoch. The use of the piezoelectric signal as a trigger event, rather than the EMG onset could therefore be questioned. However, the burst of EMG activity linked to pen or mouse movements could not always be detected in the single records and, even when detected, its onset could not reliably be identified. A well defined event like the trigger pulse generated by the piezoelectric sensor was therefore used. It should be noted that the EMG bursts shown in Fig. 3.30 are the averages of 20 single events, and that they are triggered on the pen down or mouse click at T0. The latency of the EMG burst peak (still referenced to T0) was also measured, which is assumed to represent the recruitment of enough muscle fibres to perform the actual movement. Both onset and peak latencies did not differ between the pen and mouse drawing start movement, so it may be concluded that the biological and mechanical delays were similar in the two drawing conditions.

3.4.3.2 The pre-movement events

The largest differences between freehand pen and mouse vectorial drawing took place in the 500 ms time window preceding T0. These are best illustrated in the two grand average traces of Fig. 2.29. The freehand trace is well above the baseline for the whole length of the pre T0 window, increasing in amplitude until the N-150 peak, where the signal reverses its polarity and forms the easily visible P-40 peak. However, the mouse trace in the same time span is of very small amplitude and is mainly below the baseline, with either N-150 and P-40 peaks barely visible (see Fig. 2.29 sites labelled as N-150 and P-40 in the top trace and marked with a question mark in the bottom trace).

Additional information about cortical activity may come from the computation of areas under curve. We are dealing here with spontaneous activity of cortical neurons aimed at generating pulses mainly directed to hand and forearm muscles. Although some synchronization of such activity is obvious, generation of the motor volley unavoidably takes a comparatively long time. Amplitude measurement of single peaks only assesses discharges that are simultaneous, when their extracellular potentials can be summated. This is not occurring in our case, and a more reliable measurement of the whole neuronal activity within a given span of time is provided by the measurement of the area under curve (Jorge et al., 2019; Stålberg et al., 2019). Fig. 3.29 shows a summary of our observations depicted by the grand average with areas under curve marked with colours according to sectors. Both the mean area values calculated across subjects (Table 3.3) and the coloured areas shown in Fig. 3.29 indicate that activity of the cortical neurons situated in the neighbourhood of the central sulcus was very different for the whole examined time. The hypothesis is that, in the case of pen drawing, a comparatively large population of neurons was discharging in preparation of the movement, whereas before the mouse movement, the number of discharging neurons would have been much smaller.

3.4.3.3 The post-movement events

The two traces of Fig. 3.29 look more similar each other in the post-T0 window. The N+30 peak looks larger in the pen than in the mouse drawings, due to a much larger amplitude of the paired P-40/N+30 peaks. Evaluation of areas confirm that there is a difference between the two conditions, though not as large as the one seen in the pre-T0 period. These events are mainly linked to the cortical activity evoked by somatosensory afferents (Kornhuber and Deecke, 1965b), and it is possible that components of this part of the EEG may be affected by the drawing modality as well. A dedicated analysis of these events is the object of the Experiment 3 and reported in Part 3.

3.4.3.4 Meaning of differences and similitudes of MRPs after freehand and mouse drawing

The slow and long lasting MRP negative going event (denoted N-150, see Figure 3.29 top trace) can only be seen in freehand pen drawing and very likely depends on activity of cortical neurons preparing a salient skillful movement. We found that it was missing or strongly reduced during mouse vectorial drawing, in the same way that had been previously found with simple meaningless pen tapping (Leandri et al., 2021). This evidence implies a similarity in cortical activity between mouse vectorial drawing and simple tapping, where there is no obvious activation of the pool of cortical neurons that are recruited when planning a freehand drawing. There is a chance that holding the pen and clicking the mouse might have produced movements so dissimilar as to explain the differences seen in our MRP recordings. However, the analysis of EMG reveals that there were no significant differences in the activation of the monitored forearm muscles which implies they were doing the same amount of work. We therefore believe that there is sufficient evidence to suggest that the differences found in the EEG traces could be related to the cognitive aspects of movements.

3.4.3.5 Limitations of the study

The main limitation of the study is the lack of information about the spatial distribution of EEG potentials. Only one single derivation was used which could only provide evidence relating to the site of the active electrode (C3). The electrode is actually placed midway between the motor and sensory projection of the hand on the cortex, over the central sulcus (Jasper, 1958) and picks up cortical activity from the motor and somatosensory primary areas on the dominant hemisphere. A study with more electrodes would have been desirable, but we decided to give priority to detection of differences between the two drawing conditions and used the electrode site that had been demonstrated most suitable to pick up both pre and post movement EEG events in similar conditions (Gerloff et al., 1997; Leandri et al., 2021), without hampering freedom of movements. Further research on this topic should include the investigation of the spatial distribution of the EEG responses to be compared with fNMR imaging results as recently reported in observational drawing (Katz et al., 2021). Another limit possibly lied in the two tasks, which apparently did not fully require creativity, as the subjects were just asked to trace over a figure. For the moment it was desirable to introduce as few variables as possible in the experiments, to make sure that the EEG responses were linked to an identifiable factor. A difficult task involving more decision making would have provided a number of unknown factors with consequent difficulties in interpretation of results. Finally, although the subjects participating to the research were experienced in using the digital tablet and mouse for both types of drawing, some of them might have greater experience in one of the two drawing methods. However, the relevant and consistent MRP differences strongly suggest that they are due to the cognitive involvement related to the task rather than occasional familiarity with one of the two methods.

3.4.3.6 Conclusion

The movements investigated were the same as those performed in a real design process by using a computer and the appropriate interface. The digital graphic tablet, with a raster software application, allows the use of a pen to trace signs in an almost identical mode as on paper. These drawing instruments have been developed to the point where they are now considered to be just a new medium for freehand drawing (Richards, 2013). This method of drawing combines the advantages of digital methods, such as storage of artwork, ease of reproduction and transmission, and convenience of editing with the pleasurable haptic experience of creation by the movement of the hand. As Richards said, the '"Digital freehand" is not an oxymoron' (Richards, 2013). CAD represents the other extreme of digital design, where data are transferred to computer by simple clicks and moves of the mouse while all calculations and most of the drawing are performed by the software. The convenience and time saving of CAD has brought it to universal success , but such advantages come at a price. The software has no imagination, and only does what it has been programmed for. The users therefore adapt their projects to the capabilities of the software, giving up ideas and solutions that could not be dealt with. Such bottleneck discourages originality. And the very simplicity of the mouse handling gestures deprives the mind of haptic and proprioceptive afferents that many scholars considered essential to the birth of new ideas. We believe that our research may have provided some evidence about how the cerebral cortex behaves in the two above situations, concluding that significantly more neurons are activated in freehand drawing The next challenge should be to demonstrate that those neurons are involved in a creative process more successful than in CAD and mouse handling.

3.5 Experiment 3. The EEG recording of perceived movement: Somatosensory (SEPs) and Evoked Related Potentials (ERPs) of haptic afferents from the drawing hand.

These experiments were aimed at recording the neuronal activity evoked on the contralateral brain cortex by movements performed by the hand in freehand and CAD drawing. The working hypothesis was that freehand drawing would evoke a larger cortical activity possibly linked to an increased cognitive status producing more creative results. The investigation has been exclusively focused on the post movement events. Although the time interval following the start of movement had been taken into consideration also in the experiments 1 and 2, no detailed investigation had especially been set up to that end. In the present experiment, the recorded signal was handled to obtain high definition in the time domain, so that even the early and fast components of the sensory evoked potentials could be examined. These would be used as a reference both as in amplitude and timing for the following components, reflecting the cognitive activity of non primary areas of the cortex. The higher definition of the signal would also help in detecting more subtle differences in the later components of the responses after movement. The general setup of the experiments is summarized in Fig. 3.31, and is very similar to the one used in experiments 1 and 2, but for the piezoelectric sensors, that were modified for improved precision. Description of the cortical responses to somatosensory inputs has been provided in section 3.1.13 (Haptic perception detected by SEPs and ERPs). It is worth reminding here that the first part of the SEP (components N20 and possibly P30) is the reflection of the arrival of the sensory volley on the parietal cortex (primary sensory area) and only related to the characteristics of the stimulus. Later components are due to subsequent cortical processing and dependent on the level of cognition (Desmedt et al., 1983). The different properties of the later components prompted neurophysiologists to call them also “event related potentials” (ERPs), meaning that there is not a direct link to the stimulus but that they are just more or less loosely “related” to the stimulus and that their parameters, like latency and amplitude, are mainly due to brain processing (Luck, 2014). For such reasons, the ERPs have been used to investigate the subjective reactions to stimuli during psychologically relevant tasks (Luck, 2014). Given the relevance on the hand movements with respect to cognitive functions like creativity, it seemed worthy to explore how ERPs evoked by hand movements could be affected by challenging tasks during freehand drawing in this third experiment.

3.5.1 Materials and methods

3.5.1.1 Subjects

Six subjects have been studied, 4 females and 2 males, aged between 25 and 35 years, all of them right handed . They were familiar with digital freehand drawing on tablets and with CAD design. Our work has been carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans. All subjects provided informed consent to the procedure and handling of data.

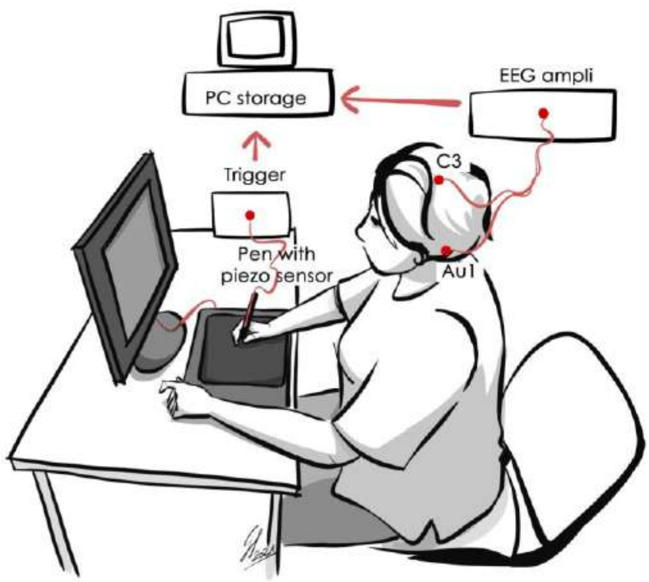

Figure 3.31. Setup of the experiment. The subject either draws freehand with tablet and pen or inputs coordinates with mouse for CAD designing. The EEG is recorded during the procedure and analysed offline. Drawing by the author.

3.5.1.2 Somatosensory and Event Related Potentials

The equipment was tuned in order to record both the fast/early sensory components of the cortical activity evoked by movement (SEPs) and the later event related potentials (ERPs). Only one derivation was used with a single electrode on the scalp over the contralateral parietal hand sensory area (C3 position according to the 10-20 international system) referred to ipsilateral ear (Au1). The signal was fed into low noise amplifiers, with filters set at a bandpass of 0.1-2000 Hz (much broader than the usual bandpass for ERPs, in order to allow recording of the fast SEP components as well). It was sampled at 50 KHz with an analog to digital (A/D) converter and streamed to a hard disc using a dedicated application. Recording derivation and equipment for signal processing are shown in Fig. 3.31.

In order to record the ERPs, a synchronizing, or "trigger", signal is necessary to mark the moment that the sensory message starts travelling from the receptors directed to the cortical areas. Since that travelling time is always expected to be the same, it is possible to apply the technique of "averaging" in order to enhance the ratio between the "signal" (i.e. all components of the EEG that are time locked to the stimulus) and the "noise" (i.e. the components of the EEG due to spontaneous random activity not time related to the stimulus). The statistical technique of averaging is often applied to electric signals and is based on the principle that, given a sufficient number of repetitions, all signal components not time locked with the trigger will eventually reduce to zero, only leaving the synchronized components with their original amplitude. In our experiments, the trigger signal was generated by a piezoelectric sensor attached to the tablet pen, as already described in a previous paper…(Leandri et al., 2021). A similar sensor was attached to the left button of the mouse, to be used in the CAD session. The acquisition of at least 200 repetitions was necessary to obtain a signal to noise ratio sufficient to detect reliable ERPs. The recorded signals were processed off-line first with a zero latency shift software filter (second order Butterworth, 0.1-200Hz) and then averaged. Amplitudes of peaks were calculated in microvolts and referred to the baseline. A "grand average" (i.e. the average of all the averages obtained in the single recording sessions) was performed, as customary in ERPs technique (Luck, 2014) to compensate for inter-subject variability and provide a summary of the signal trend.

Figure 3.32. Photograph of cityscape to be used for task 1, freehand drawing. Medieval porticos of the waterfront, Genova. Photograph by the author

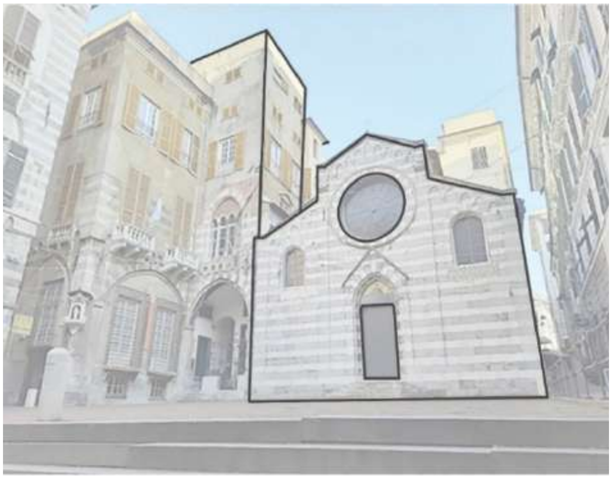

Figure 3.33. Photograph of cityscape to be used for task 2, CAD design. The medieval piazza San Matteo, Genova. Photograph by the author.

3.5.1.3 The Tasks

Two drawing tasks were required to the participants. The first task (Task 1) was to perform a freehand drawing tracing over a cityscape picture that was presented on a low opacity background layer of the drawing (Fig. 3.32). They were asked to keep the pen just hovering on the tablet when resting, and touch the tablet surface with short drawing strokes. Touching the tablet with the pen would generate the trigger signal and the acquisition of the EEG signal from the scalp, containing the ERP. Drawing with short strokes would assure that a sufficient number of EEG epochs (at least 200) were stored to be averaged. The free raster software GIMP 2.10.30 for Windows was used for freehand drawing on a Intuos© PTK-640 tablet (Wacom Co. Ltd., Saitama, Japan) equipped with a Wacom KP-501E-01 pen to which the piezoelectric sensor was attached. Tablet and pen are shown in Fig. 3. The second task (Task 2) was to trace over a similar cityscape (Fig. 3.33) by CAD drawing, using mouse and the Autocad © (Autodesk, San Rafael, California, USA) student version. In order to trace lines the left button of the mouse had to be kept pressed, which generated a trigger signal used for the ERP acquisition and further processing, like in Task 1.

3.5.2 Results and discussion

3.5.2.1 Freehand drawing

When subjects drew freehand, a complete set of the ERP components could be recorded (Fig. 3.34 top set and Fig. 3.35, top trace). The first components that we could see in our recordings was the negative-positive complex N20/P30, which reflects the activity of sensory neurons that are first activated upon the arrival of the afferent impulses on the cortex. Further than this, all the subsequent components, due to cortical processing, were all clearly visible. Their mean latencies and amplitudes are reported in Table1. It is of notice that N 50 and N120 had a particularly high amplitude. These components are affected by attention and relevance of the stimulus, whilst the following components P200, N300 and P400 are thought to be linked to emotively relevant decisional processes (Desmedt et al., 1983; Hillyard et al., 1973). It may be concluded that in freehand drawing the sensory afferents from the hand provided information about the executed movement, as attested by the occurrence of the N20/P30, and later on gave rise to a strong attentive process, most probably independent from the explicit will of the drawer and preceding any conscious decision.

	ms	N20	P30	N50	P70	N120	P200	N300
Freehand	mean	19.9	30.5	48.6	67.8	115.1	184.3	270.3
	Sd	0.5	3.0	4.1	2.9	5.3	4.3	8.1
CAD	mean	19.6	29.83	52.6	69.8	118.6	198.1	272.3
	Sd	0.3	2.3	5.7	9.1	5.2	16.0	16.2

Table 3.4. Mean values in ms of latencies of the main ERP components evoked by the freehand movements, compared to latencies during CAD design. There are no statistically significant differences between the two conditions.

	mV	N20	P30	N50	P70	N120	P200	N300
Freehand	mean	1.7	0.9	3.6	1.8	4.8	2.0	2.9
	Sd	0.9	0.3	2.5	1.2	1.5	1.1	2.5
CAD	mean	1.6	0.9	1.1	0.5	0.9	0.5	0.5
	Sd	0.6	0.6	0.3	0.5	0.6	0.4	0.2
% decrmt		6%	2%	*69%	*68%	*80%	*73%	*83%

Table 3.5. Mean absolute values in μV of peak to baseline amplitudes of the main ERP components during freehand and CAD drawing. The last row shows the percentage in decrement (%decrmnt) in amplitude, taking the freehand condition as 100% amplitude. The first two components N20 and P30 do not show any statistically significant difference. All the subsequent components show a significant decrease in amplitude ($p<0.05$, marked with an asterisk).

3.5.2.2 CAD design with mouse

With this design modality the first two components (N20 and P30) could be recorded with very similar characteristics of latency and amplitude as in freehand drawing. However, as reported in Table2, the subsequent components were strongly reduced, starting from the N50 (Fig.3.34 bottom set, and Fig. 3.35, bottom trace). So, the first part of the ERP was unchanged between Task1 and Task2, whereas the second part was dramatically different. The N20/P30 represents the exogenous part of the ERP (Desmedt et al., 1983; Luck, 2014) and it is just a sort of passive transmission of the information about movement originating from the muscle and joint receptors of the hand. It tells us that in both cases that the kynematics of the movement were not too dissimilar. On the other hand, when the components reflecting cortical cognitive processes were involved, striking differences could be observed. N50 could still be recorded in CAD design, but approximately than halved in amplitude. The N120 was much more reduced, meaning that attentional cognition in CAD was almost lacking; even worse, the following components, linked to decisional cognition, almost could not be observed any more, possibly meaning that the process of designing with CAD aroused little attention and even less emotively pregnant decision making.

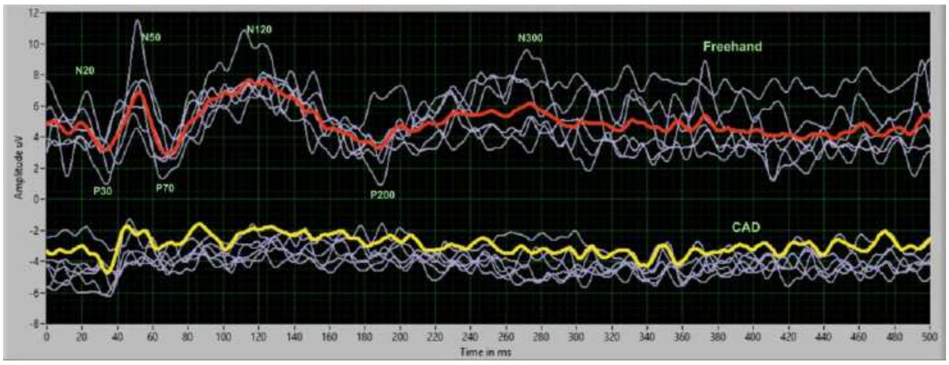

Figure 3.34. The upper set of traces relates to task 1: freehand drawing. It shows the 6 averages of the single subjects with superimposed the grand average, where the ERP components are labelled. The lower set shows the averaged recordings and grand average related to 2 with CAD design. Amplitude of ERPs late components are much reduced in task 2. The red and yellow traces are the grand-average of the greyed single averages. Negativity is upwards. Image by the author.

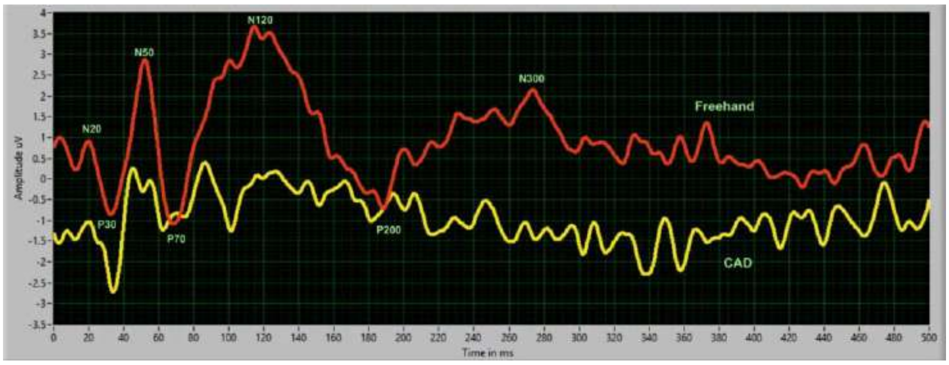

Fig3.35. Details of the grand averages related to task 1 (upper red trace) and task 2 (lower yellow trace) showing that the early components (N20 and P30) are unchanged, whilst the late components, from N50 onwards are strongly reduced during CAD design. Image by the author.

3.5.2.3 Conclusion

The results of this work provide instrumental evidence that the haptic sensory afferents from the hand are linked to a different cognitive status during freehand drawing and CAD design. The recorded ERP components can be categorised in two groups: a first one, consisting of the N20/P30 pair, unchanged across the two tasks, and a second one, consisting of the N50 and subsequents, which is task-affected. The ERPs that we recorded are assimilable to the SEPs early and late components reviewed by Desmedt (Desmedt et al., 1983) The first component pair N20/P30 is comparable with the peak pair N20-P25 of the somatosensory evoked potentials (SEPs); it reflects the activation of the primary sensory cortex and is unaffected by attention or other cognitive states. It is also known that the subsequent components of SEPs are very much dependent on the state of attention and possibly other current cognitive conditions of the subject. Such components originate from associative areas of the brain cortex, where the sensory perception is processed according to the subject disposition. With such premises, it is understandable that the pair N20/P30 in our recordings did not change between freehand drawing and CAD task, because it brought an elementary information to that part of the cortex which is not deputed to heavy processing. But the strong reduction in amplitude of the later components during CAD design is a token of the very different state of mind related to the two situations. From a functional point of view, it is likely that a much larger and specific amount of neuronal activity was recruited in our experiments during freehand drawing. Although we only recorded from the parietal cortical area dedicated to the processing of afferent activity, which just acts as a receiver structure, it is worth noting that the same cortex also has important links with the supplementary motor area and prefrontal areas, where new ideas may be borne, possibly facilitating the process of divergent thinking, preliminary to increased creativity.

3.6 Conclusions from the three experiments.

The evidence provided by the experiments reported in this thesis is a first step in support of the cognitive engagement provided by freehand drawing. Although the raw data only relate to amplitudes, areas and energy of some EEG components, it is possible to infer that their variations are linked to the saliency of the hand movements time locked to the EEG. The high temporal definition and reliability of the scalp recorded electric events allows to differentiate what happens before and after movement. Such information is important because the preparation of movement is probably directly linked to creativity, which is a cognitive function of a high level order, the outcome of more elementary constituents of mental process. On the other hand, the '*primum movens*', or first cause of the insight leading to creativity may not originate casually by neuronal spontaneous discharge, but from a peripheral outside stimulus, which could be represented by the sensory inputs from the hand haptic receptors. In this cause-effect sequence, the hand movement and grasping of a tool (the pencil) could well initiate a cascade of events recruiting neurons and taking to creativity and the end product craft. An apparent paradox takes place, that the sensory afferents, which in the EEG come after movement, are actually the starting point of the whole creative process. Obviously, drawing, or making a craft is not something done in one single strike, but implies a huge number of movements, so the input generated by a previous movement may well be a mentor for the next.

GENERAL CONCLUSIONS AND FUTURE RESEARCH

General Conclusions and future research

4.1 The observer's eye

4.2 The draftsman's brain
4.2.1 From paper to tablet: creativity in design
4.2.2 Exploring neurons in action. How far can we go?
4.2.3 Can creativity be boosted?

4.3 Future research

4.1 The observer's eye

The observer's eye is at the very end of the designer-communication-observer chain and it is the final aim of the design process; its relevance is paramount. We are now aware of the brain structures involved in visual perception, but any forecast is hampered by the huge amount of internal and external variables impinging on the higher cognitive processes and decisional stages. The observer's opinion relies not only on the intrinsic properties of the image but on esthetic, cultural, social, ethical, and economic factors currently trending. Though, of course, the starting point still remains the image. The designer must communicate through it, embedding a pregnant artistic message which should stand out from the less relevant details. As we have seen from the results of the reported Communication and Recognition tests, this aim is best achieved by the hand drawn design. Through a well conceived message it is possible to somehow direct the observer's opinion, prevailing on the other influencing factors. In this context, the photorealistic renders may best meet the observer's need for realism and agreeability, but still not be able to communicate the desired message clear enough, making of it a weak signal in a noisy environment. The brain mechanisms underlying visual perception and psychology have been reviewed in Part 2 and it is worth reminding here that at least some fundamental constituents of the designer's ideas may be embedded into the hand drawn message at unconscious level. They are also retrieved by the observer at the same level. Such constituents my therefore proceed undetected by conscious inhibition straight to the decisional level and exert a stronger influence on the final opinion.

4.2 The draftsman's brain

4.2.1 From paper to tablet: creativity in design

Any kind of design needs to have an incipit, tightly linked to creativity. Any kind of design needs to have an incipit, tightly linked to creativity. The first part of the thesis has dealt with the different types of drawings with their aims and the employed techniques. From the initial sketch to the last stages of a project, from the first still undefined shape to the strong realism of the detailed representation, it appears obvious that the designer needs to use a medium which suits the evolution of ideas and their agreeable graphic representation. Still today pencil and paper, for their flexibility, handiness and simplicity, are widely used for those architectural representations where the artistic side is meant to be prevalent. For other types of design, the use of computers is unavoidable, but creativity may then be limited, because of the restraints of the instrument.

For such reason, the CAD mechanistic approach to design is starting to be criticized and a return to freehand drawing is though necessary to boost creativity. Several essays have already been quoted in this thesis claiming that freehand drawing nurtures original ideas in design and that sketching has inherent ambiguity strongly encouraging divergent thinking by proposing a number of design solutions to a problem. The neurophysiological experiments reported here support such claims, which so far had only been based upon indirect empirical evidence. Just as the drawing implements had evolved through the centuries, so the digital tablets should be regarded as a novel drawing medium that can blend the perception and creativity of the freehand drawing on paper with the commodities offered by the computer. We may well assert that freehand digital drawing is not an 'oxymoron', but a new method still maintaining the creativity necessary to any design.

4.2.2 Exploring neurons in action. How far can we go?

Functional exploration of the brain is now evolved to the point that subtle changes in electric activity and blood perfusion can be detected reflecting perception, movement intention, cognitive and emotional conditions. The advantages and pitfalls of the current technology have been briefly reviewed in this thesis, suggesting that the most direct methods to detect activity of the brain are those related to the electric properties of the excitable neuronal membranes. In practical terms, we re now capable of reliably following the neuronal messages from the sensory organs to the brain, and from the brain to the motor effectors, but as far as the cognitive processes are concerned, although we can detect changes in activity we may just have an approximate idea of their mechanisms. Nevertheless, we do know enough about connections of brain areas to postulate reasonable hypotheses that can be tested in the experimental environment. Creativity, is one of the most difficult cognitive functions that can be explored, mainly because it comes from the merging of many other functions. The results provided by the experiments reported in this thesis provide simple answers to a very basic question, that is whether the cerebral activity is increased or not when tasks demanding some sort of creativity are performed. The answer is affirmative and it may be added that there are definite time relationships between the type of brain activity and the actions performed by the subject under investigation. Such answers relate to events that are assumed to be the basis of creativity, although do not relate to creativity itself. With the present state of technology it is unlikely that investigations may be brought at a deeper level of neuronal activity. Though a further development of this research is certainly possible by tuning the tasks submitted to the various subjects.

4.2.3 Can creativity be boosted?

Though dependent on many factors, genetic and environmental, creativity is determined by contingent elements by which it may be boosted or depressed. The notion that some psychologically demanding activity may boost creativity has been asserted many times cross centuries, and supported by the experiment on somatosensory evoked potentials reported in this thesis. Salient movements of the hand are followed by much larger brain activity than meaningless movements. This is a possible evidence that movements of the hand, may, given favourable conditions, be at the root of cerebral activity linked to creativity.

4.3 Future research

The questionnaire that has been submitted through the Web has demonstrated that it is worth investigating *objective* elements of the images and perceptions in order to have a complete idea of their usefulness and impact. Along this line, more study will be dedicated in order to better define which qualities of the image could be qualified as objective and how could be explored. Consequently, further questionnaires will be developed and submitted either locally to the academic world, and on the Web.

The neurophysiological experiments so far performed for this thesis involve a new methodology aimed at recording movement related brain activity during freehand or CAD drawing. Such application had not been used before and therefore most of the effort has ben spent in developing and testing an optimal technique to that end. After this first aim has been accomplished, two subsequent steps have been performed to assess whether the brain activity would correlate with the saliency of simple tasks, comparing freehand versus CAD drawing. The results obtained are evidence enough to suggest that creativity may be boosted by freehand drawing. It is expected that more elaborate drawing tasks may address cognitive aspects of creativity in a more specific manner, hereby further substantiating the claim about freehand drawing. The next research planned to this end will involve a more *creative* task than the past ones, as the subjects will be asked to develop a presentation image starting from a roughly sketched design. One group will use freehand drawing on a digital tablet, and the CAD drawing with mouse. It is expected that the recordings will indicate that the freehand drawing will be linked to increased brain activity.

Conclusiones generales y futuras investigaciones

4.1 El ojo del observador

4.2 La función cerebral del diseñador

4.2.1 Del papel a la tableta: la creatividad en el dibujo
4.2.2 Exploración de neuronas en funcionamiento. ¿Hasta dónde podemos ir?
4.2.3 ¿Se puede potenciar la creatividad?

4.3 Investigaciones futuras

4.1 El ojo del espectador

El ojo del observador está al final de la secuencia diseñador-comunicación-observador y es el objetivo final del proceso de diseño; su relevancia es fundamental. Hoy en día conocemos las estructuras nerviosas involucradas en la percepción visual, pero cualquier patrón se ve obstaculizado por la enorme cantidad de variables internas y externas que afectan los procesos cognitivos y las etapas de toma de decisiones. La opinión del espectador se basa no sólo en las propiedades intrínsecas de la imagen, sino en factores estéticos, culturales, sociales, éticos y económicos actuales. Aunque, por supuesto, el punto de partida sigue siendo la imagen. El diseñador debe comunicar a través de él, incorporando un mensaje artístico preñado que debe surgir de los detalles menos relevantes. Como hemos visto a partir de los resultados de las pruebas de Comunicación y Reconocimiento informados, este objetivo se logra mejor con el dibujo hecho a mano. A través de un mensaje bien concebido es posible de alguna manera orientar la opinión del observador, prevaleciendo sobre los demás factores que pueden influir en ella. En este contexto, las representaciones fotorrealistas pueden satisfacer mejor la necesidad de realismo y amabilidad del observador, pero aun así no pueden comunicar el mensaje deseado con la suficiente claridad, por lo que la señal comunicativa será de baja intensidad, apenas distinguible del ruido. Los mecanismos cerebrales que subyacen a la percepción visual y la psicología se examinaron en la Parte 2 y vale la pena mencionar aquí que al menos algunos componentes fundamentales de las ideas del diseñador se pueden incorporar en el mensaje dibujado a mano en un nivel subconsciente. El observador probablemente los percibirá en el mismo nivel inconsciente. Estos elementos constitutivos del mensaje pueden operar directamente en el nivel cognitivo de la toma de decisiones y ejercer una influencia muy significativa en la opinión final.

4.2 La función cerebral del diseñador

4.2.1 Del papel a la tableta: la creatividad en el dibujo

Todo tipo de diseño arquitectónico debe tener una apertura, fuertemente ligada a la creatividad. El excursus de la primera parte de esta tesis destacó los diversos tipos de dibujo, sus propósitos y las técnicas utilizadas. Tanto en la parte inicial del boceto como en las etapas finales que ilustran el objeto en detalle, se hizo evidente la necesidad del diseñador de utilizar un medio adecuado para la rápida evolución de las ideas y su satisfactoria representación gráfica. Incluso hoy en día, para bocetos y otro tipo de ilustración donde se pretende hacer prevalecer el lado artístico, el lápiz y el papel son muy utilizados por su indiscutible flexibilidad y facilidad de manejo. Para otros tipos de dibujo, el uso del PC es inevitable, pero puede crear límites a la libertad creativa, debido a sus restricciones técnicas y manuales.

Por esta razón, el enfoque CAD mecanicista del diseño ahora está comenzando a ser criticado y se considera necesario volver al dibujo a mano alzada para estimular la creatividad. En esta tesis ya se han citado varios escritos que creen que el dibujo a mano alzada puede dar lugar a ideas originales en el diseño y que el dibujo a boceto tiene una ambigüedad intrínseca que fortalece el pensamiento divergente al proponer una amplia gama de soluciones de diseño. Los experimentos neurofisiológicos informados aquí brindan evidencia científica para tales conceptos, hasta ahora basados solo en evidencia empírica indirecta. Se puede suponer que las tabletas gráficas digitales pueden considerarse el anillo más reciente de las herramientas de dibujo a mano alzada: permiten fusionar la percepción y la creatividad del dibujo sobre papel con las posibilidades que ofrece el ordenador. Bien se puede decir que el dibujo digital a mano alzada no es tanto un 'oxímoron', sino un nuevo método que conserva y quizás aumenta la creatividad necesaria para el nacimiento de cualquier proyecto.

4.2.2 Exploración de la función neuronal. ¿Hasta dónde podemos ir?

La exploración funcional del cerebro ahora ha evolucionado hasta el punto en que es posible detectar cambios sutiles en la actividad eléctrica y la perfusión sanguínea que reflejan la percepción, la intención de moverse, las condiciones cognitivas y emocionales. Las ventajas y desventajas de la tecnología actual se han examinado brevemente en esta tesis, lo que sugiere que los métodos más directos para detectar la actividad cerebral son los relacionados con las propiedades eléctricas de las membranas neuronales excitables. En términos prácticos, ahora podemos rastrear de manera confiable los mensajes neuronales desde los órganos sensoriales hasta la corteza cerebral y desde la corteza motora hasta los efectores musculares, pero en lo que respecta a los procesos cognitivos, aunque los cambios en la actividad cerebral son detectables, podemos tener solo una idea aproximada de los mecanismos relacionados. Sin embargo, tenemos suficiente información sobre las conexiones de las áreas del cerebro para postular suposiciones razonables que pueden probarse en el entorno experimental. La creatividad es una de las funciones cognitivas más difíciles de explorar, principalmente porque surge de la fusión de muchas otras funciones. Los resultados proporcionados por los experimentos reportados en esta tesis brindan respuestas simples a una pregunta muy básica, a saber, si la actividad cerebral aumenta o no cuando se realizan tareas que requieren algún tipo de creatividad. La respuesta es afirmativa y se puede agregar que existen relaciones temporales precisas entre el tipo de actividad cerebral y las acciones realizadas por el sujeto investigado. Tales respuestas se refieren a eventos que se supone que son la base de la creatividad, aunque no están directamente relacionados con la creatividad en sí. En el estado actual de la tecnología, es poco probable que las investigaciones de la actividad neuronal se puedan seguir investigando, aunque ciertamente es posible un mayor desarrollo de esta investigación perfeccionando las pruebas de diseño propuestas para los diversos sujetos.

4.2.3 ¿Se puede potenciar la creatividad?

Aunque depende de muchos factores, genéticos y ambientales, la creatividad está determinada por elementos contingentes a partir de los cuales puede ser estimulada o deprimida. La idea de que ciertas actividades psicológicamente exigentes pueden aumentar la creatividad ha sido afirmada muchas veces a lo largo de los siglos y validada por el experimento sobre potenciales evocados somatosensoriales informado en esta tesis. Los movimientos salientes de las manos son seguidos por una actividad cerebral mucho mayor que los movimientos sin sentido. Esta es una posible evidencia de que los movimientos de la mano, en condiciones favorables, pueden estar en la base de la actividad cerebral vinculada a la creatividad.

4.3 Investigaciones futuras

El cuestionario que se propuso a través de la Web ha demostrado que vale la pena investigar los elementos objetivos de las imágenes y la percepción para hacerse una idea completa de su utilidad e impacto. Continuando en esta dirección, se planean más estudios para definir mejor las cualidades de la imagen que podrían calificarse como objetivas y cómo podrían explorarse. Como resultado, se desarrollarán más cuestionarios para la academia local y la web.

Los experimentos neurofisiológicos realizados para esta tesis utilizaron una nueva metodología destinada a registrar la actividad cerebral relacionada con el movimiento durante el dibujo a mano alzada o con CAD. Esta técnica nunca se había utilizado antes y una parte importante del esfuerzo experimental se dedicó al desarrollo y validación de una metodología óptima.Tras la consecución de este primer objetivo, se realizaron dos pasos posteriores; primero se evaluó si la actividad cerebral podía correlacionarse con la relevancia cognitiva en la ejecución de tareas sencillas, y luego se comparó el dibujo a mano alzada con el de CAD. Los resultados obtenidos proporcionaron evidencia experimental en apoyo de la hipótesis de que la creatividad puede mejorarse mediante el dibujo a mano alzada. Es posible creer que la ejecución de tareas más elaboradas, siempre en el contexto del dibujo, puede esclarecer los aspectos cognitivos de la creatividad de forma más específica. La próxima investigación diseñada para este propósito supondrá una tarea que implica una mayor creatividad que las anteriores, ya que se pedirá a los sujetos que desarrollen una imagen de diseño a partir de un dibujo esbozado a modo de boceto. Un grupo utilizará el dibujo a mano alzada en tableta digital y el otro el dibujo CAD con el ratón. Se espera que las grabaciones indiquen que el dibujo a mano alzada estará relacionado con una mayor actividad cerebral.

Conclusioni generali e ricerche future

4.1 L’occhio dell’osservatore

4.2 La funzione cerebale del disegnatore

4.2.1 Dalla carta alla tavoletta grafica: creatività nel disegno
4.2.2 Esplorazione dei neuroni in funzione. Fino a dove ci possiamo spingere?
4.2.3 La creatività può essere incrementata?

4.3 Ricerca futura

4.1 L'occhio dell'osservatore

L'occhio dell'osservatore è al termine della sequenza designer-comunicazione-osservatore ed è l'obiettivo finale del processo progettuale; la sua rilevanza è fondamentale. Al giorno d'oggi siamo consapevoli delle strutture nervose coinvolte nella percezione visiva, ma qualunque schema è ostacolato dall'enorme quantità di variabili interne ed esterne che incidono sui processi cognitivi e sugli stadi decisionali. L'opinione dell'osservatore si basa non solo sulle proprietà intrinseche dell'immagine, ma su fattori estetici, culturali, sociali, etici ed economici attuali. Anche se, ovviamente, il punto di partenza rimane ancora l'immagine. Il designer deve comunicare attraverso di essa, inglobando un messaggio artistico pregnante che deve emergere dai dettagli meno rilevanti. Come abbiamo visto dai risultati dei test di Comunicazione e Riconoscimento riportati, questo obiettivo viene raggiunto al meglio dal disegno fatto a mano. Attraverso un messaggio ben concepito è possibile in qualche modo orientare l'opinione dell'osservatore, prevalendo sugli altri fattori che la possono influenzare. In questo contesto, i render fotorealistici possono soddisfare al meglio il bisogno di realismo e gradevolezza dell'osservatore, ma non essere comunque in grado di comunicare il messaggio desiderato in modo sufficientemente chiaro, per cui il segnale comunicativo sarà di bassa intensità, poco distinguibile dal rumore di. I meccanismi cerebrali alla base della percezione visiva e della psicologia sono stati esaminati nella Parte 2 ed è opportuno ricordare qui che almeno alcuni componenti fondamentali delle idee del designer possono essere incorporati nel messaggio disegnato a mano a livello inconscio. L'osservatore li percepirà probabilmente al medesimo livello incosncio. Tali elementi costitutivi del messaggio possono operare direttamente sul livello cognitivo decisionale ed esercitare un'influenza molto rilevante sull'opinione finale.

4.2 La funzione cerebrale del disegnatore

4.2.1 Dalla carta alla tavoletta grafica: creatività nel disegno

Ogni tipo di disegno architettonico deve avere un incipit, fortemente legato alla creatività. L'excursus della prima parte di questa tesi ha messo in luce le varie tipologie del disegno, le sue finalità e le tecniche utilizzate. Sia nella parte iniziale dello sketch sia nelle fasi conclusive che illustrano l'oggetto nei dettagli, è apparsa evidente la necessità da parte del disegnatore di utilizzare un medium confacente alla rapida evoluzione delle idee e alla loro soddisfacente rappresentazione grafica. Ancora oggi, per gli sketch e altri tipi di illustrazione dove l'intento è di far prevalere il lato artistico, sono ampiamente utilizzate carta e penna per la loro indiscutibile flessibilità e maneggevolezza. Per altri tipi di disegno il ricorso al pc è inevitabile, ma può creare limiti alla libertà creativa, per le sue restrizioni di ordine tecnico e manuale.

Per tale motivo, l'approccio meccanicistico CAD alla progettazione inizia ora ad essere criticato e si ritiene necessario un ritorno al disegno a mano libera per stimolare la creatività. In questa tesi sono già stati citati diversi scritti ritenenti che il disegno a mano libera possa dare luogo a idee originali nella progettazione e che il disegno a schizzo abbia un'ambiguità intrinseca che potenzia il pensiero divergente proponendo una vasta serie di soluzioni progettuali. Gli esperimenti neurofisiologici qui riportati forniscono prove scientifiche di tali concetti, finora basati solo su prove empiriche indirette. Si può ritenere che le tavolette grafiche digitali possano essere considerate l'anello più recente degli strumenti per il disegno a mano libera: permettono di fondere la percezione e la creatività del disegno su carta con le possibilità offerte dal computer. Si può ben affermare che il disegno digitale a mano libera non sia tanto un 'ossimoro', ma un metodo nuovo che preserva e forse incrementa la creatività necessaria alla nascita di qualsiasi progetto.

4.2.2 Esplorazione della funzione neuronale. Fino a dove ci possiamo spingere?

L'esplorazione funzionale cerebrale si è ora evoluta al punto che è possibile rilevare sottili cambiamenti nell'attività elettrica e nella perfusione sanguigna che riflettono la percezione, l'intenzione di movimento, le condizioni cognitive ed emotive. I vantaggi e le insidie dell'attuale tecnologia sono stati brevemente esaminati in questa tesi, suggerendo che i metodi più diretti per rilevare l'attività cerebrale sono quelli legati alle proprietà elettriche delle membrane neuronali eccitabili. In termini pratici, siamo ora in grado di seguire in modo affidabile i messaggi neuronali dagli organi sensoriali sino alla corteccia cerebrale e dalla corteccia motoria sino agli effettori muscolari, ma per quanto riguarda i processi cognitivi, sebbene siano rilevabili cambiamenti nell'attività cerebrale, possiamo avere solo un'idea approssimativa dei meccanismi correlati. Tuttavia, abbiamo abbastanza informazioni sulle connessioni delle aree cerebrali da postulare ipotesi ragionevoli che possono essere verificate nell'ambiente sperimentale. La creatività, è una delle funzioni cognitive più difficili che si possano esplorare, principalmente perché nasce dalla fusione di molte altre funzioni. I risultati forniti dagli esperimenti riportati in questa tesi forniscono risposte semplici a una domanda molto basilare, ovvero se l'attività cerebrale aumenta o meno quando vengono eseguiti compiti che richiedono una sorta di creatività. La risposta è affermativa e si può aggiungere che esistono precise relazioni temporali tra il tipo di attività cerebrale e le azioni compiute dal soggetto indagato. Tali risposte si riferiscono a eventi che si presume siano la base della creatività, sebbene non siano direttamente collegati alla creatività stessa. Allo stato attuale della tecnologia è improbabile che le indagini dell'attività neuronale possano essere ulteriormente approfondite, anche se un ulteriore sviluppo di questa ricerca è certamente possibile perfezionando le prove di disegno proposte ai vari soggetti.

4.2.3 La creatività può essere incrementata?

Sebbene dipenda da molti fattori, genetici e ambientali, la creatività è determinata da elementi contingenti dai quali può essere stimolata o depressa. L'idea che alcune attività psicologicamente impegnative possano aumentare la creatività è stata affermata molte volte nel corso dei secoli e convalidata dall'esperimento sui potenziali evocati somatosensoriali riportato in questa tesi. I movimenti salienti della mano sono seguiti da un'attività cerebrale molto maggiore rispetto ai movimenti privi di significato. Questa è una possibile evidenza che i movimenti della mano, in condizioni favorevoli, possono essere alla base dell'attività cerebrale legata alla creatività.

4.3 Ricerca futura

Il questionario che è stato proposto attraverso il Web ha dimostrato che vale la pena indagare gli elementi oggettivi delle immagini e della percezione per avere un'idea completa della loro utilità e impatto. Proseguendo in questa direzione, sono in programma ulteriori studi per definire meglio le qualità dell'immagine che potrebbero essere qualificate come oggettive e come potrebbero essere esplorate. Di conseguenza, saranno sviluppati ulteriori questionari per il mondo accademico locale e per il web.

Gli esperimenti neurofisiologici eseguiti per questa tesi hanno utilizzato una nuova metodologia volta a registrare l'attività cerebrale correlata al movimento durante il disegno a mano libera o con il CAD. Questa tecnica non era mai stata utilizzata prima e una importante parte dell'impegno sperimentale è stato dedicato allo sviluppo e alla convalida di una metodologia ottimale.. Dopo il raggiungimento di questo primo obiettivo, sono stati eseguiti due passaggi successivi; dapprima è stato valutato se l'attività cerebrale potesse essere correlata con la rilevanza cognitiva nell'esecuzione di compiti semplici, e successivamente sono stati confrontati il disegno a mano libera con quello CAD. I risultati ottenuti hanno fornito prove sperimentali in supporto dell'ipotesi che la creatività possa essere potenziata dal disegno a mano libera. E' possibile ritenere che l'esecuzione di compiti più elaborati, sempre nell'ambito del disegno, possa chiarire gli aspetti cognitivi della creatività in un modo più specifico. La prossima ricerca progettata a tal fine comporterà un compito che implichi una maggiore creatività rispetto a quelli passati, in quanto ai soggetti verrà chiesto di sviluppare un'immagine progettuale partendo da un disegno abbozzato come schizzo. Un gruppo utilizzerà il disegno a mano libera su una tavoletta digitale e l'altro il disegno CAD con il mouse. Ci si attende che le registrazioni indicheranno che il disegno a mano libera sarà collegato a una maggiore attività cerebrale.

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ANNEX 1

Annex 1: Source data for the questionnaire of Part 2

Web forms as seen by the test takers

Responses to the questions

Web Forms

Architectural Drawing 3.0
Survey Questionnaire

Description (optional)

Start press Enter ↵

1→ In which age group are you?*

Description (optional)

Type or select an option

19 and under
20-29
30-39
40-49
50-59
60+

2 → Gender:*

Description (optional)

A Male

B Female

3 → What is your current occupation?*

Description (optional)

Type or select an option

Architect
Architectural Assistant
Interior/Product Designer
Civil/Construction Engineer
Real Estate Agent
Developer
Academic (in the architectural field)
Student (in the architectural field)
3D Artist
Architectural Illustrator
Other

1. COMMUNICATION

"Marketing is no longer about the stuff that you make, but about the stories you tell."

- Seth Godin

Continue press Enter ↵

In this illustration, which building is the project?

Description (optional)

Continue press Enter ↵

4→ Pick the image/images which you think represent the building designed by the architect.*

Description (optional)

A

B

C

D

In this illustration, which building is the project?

Description (optional)

Continue press Enter ↵

5 → Pick the image/images which you think represent the building designed by the architect.*

A

B

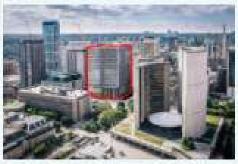
In this photo realistic render, which building is the project?

Description (optional)

Continue press Enter ↵

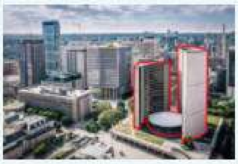
6 → Pick the image/images which you think represent the building designed by the architect.*

Description (optional)



A

B



C

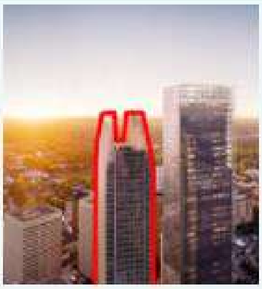
D

In this photo realistic render, which building is the project?

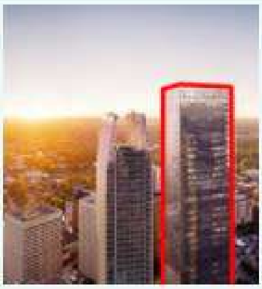
Description (optional)

Continue press Enter ↵

7→ Pick the image/images which you think represent the building designed by the architect.*



A



B

2. RECOGNIZABILITY

"You've either got or you haven't got style, and if you've got it you stand out a mile."

- Frank Sinatra

Continue press Enter ↵

These well known architects use both photo realistic and illustrations to present their projects.

Description (optional)

Continue press Enter ↵

Renzo Piano

Norman Foster

Nikken Sekkei

8→ Using the previous set of images as a reference, assign each illustration to the correct architect.*

Description (optional)

Renzo Piano

Norman Foster

Nikken Sekkei

- A 1.Piano - 2.Sekkei - 3.Foster
- B 1.Piano - 2.Foster - 3.Sekkei
- C 1.Foster - 2.Sekkei - 3.Piano
- D 1.Foster - 2.Piano - 3.Sekkei
- E 1.Sekkei - 2.Piano - 3.Foster
- F 1.Sekkei - 2.Foster - 3.Piano

9 → Using the previous set of images as a reference, assign each render to the correct architect.*

Description (optional)

Renzo Piano

Norman Foster

Nikken Sekkei

1

2

3

- A 1.Piano - 2.Sekkei - 3.Foster
- B 1.Piano - 2.Foster - 3.Sekkei
- C 1.Foster - 2.Sekkei - 3.Piano
- D 1.Foster - 2.Piano - 3.Sekkei
- E 1.Sekkei- 2.Piano - 3.Foster
- F 1.Sekkei - 2.Foster - 3.Piano

3. ENGAGEMENT

"Architecture arouses sentiments in man. The architect's task, therefore, is to make those sentiments more precise."

- Adolf Loos

Continue press Enter ↵

10 → This living room is represented with an illustration and a render. Mark which image you prefer.*

Description (optional)

A

B

11 → This bedroom is represented with an illustration and a render. Mark which image you prefer.*

Description (optional)

A

B

12→ Would you be interested in a course on architectural illustration with digital tablets?*

Description (optional)

- Y Yes
- N No

If your occupation is related to the architectural field, please answer the following two questions. Otherwise, skip to the last page.

Description (optional)

Continue press Enter ↵

14→ In which of these stages of a project do you usually use DRAWINGS / ILLUSTRATIONS?

Description (optional)

Choose as many as you like

- A Preliminar / Concept
- B Work in progress
- C Final Presentation
- D Lesson / Workshop
- E Article / Publication
- F Never

15→ If you'd like to have more info about this topic (articles, conferences, events, courses, etc.) please enter your email below.

Description (optional)

name@example.com

OK ✓ press **Enter** ↵

16→ If you like, leave your comment here.

Description (optional)

Type your answer here...

Shift ⇧ + Enter ↵ to make a line break

OK ✓ press **Enter** ↵

Thank you for your time!

Images sources on www.gaialeandri.com

Description (optional)

Responses to the form questions

#	In which age group are you?	Gender:	What is your current occupation?
1	30-39	Female	Architect
2	30-39	Female	Architect
3	30-39	Female	Other
4	30-39	Male	Architect
5	20-29	Female	Other
6	30-39	Male	Architect
7	20-29	Female	Architectural Assistant
8	20-29	Female	Other
9	20-29	Female	Other
10	30-39	Female	Architectural Illustrator
11	19 and under	Female	Student (in the architectural field)
12	20-29	Female	Student (in the architectural field)
13	20-29	Male	Architect
14	19 and under	Male	Student (in the architectural field)
15	20-29	Female	Architectural Assistant
16	30-39	Male	Architect
17	20-29	Female	Architect
18	20-29	Male	Architectural Assistant
19	30-39	Male	Civil/Construction Engineer
20	20-29	Male	Architect
21	20-29	Female	Student (in the architectural field)
22	30-39	Male	Student (in the architectural field)
23	40-49	Male	Architect
24	30-39	Male	Architect
25	20-29	Male	Architect
26	30-39	Male	Architect
27	20-29	Male	Student (in the architectural field)
28	19 and under	Female	Student (in the architectural field)
29	40-49	Male	Academic (in the architectural field)
30	20-29	Male	Student (in the architectural field)
31	30-39	Male	Civil/Construction Engineer
32	40-49	Male	Civil/Construction Engineer
33	20-29	Male	Civil/Construction Engineer
34	30-39	Male	Other
35	30-39	Male	Other
36	60+	Male	Other

37	20-29	Male	3D Artist
38	40-49	Female	Architect
39	50-59	Male	Academic (in the architectural field)
40	30-39	Female	Architect
41	20-29	Female	Architect
42	50-59	Male	Architect
43	30-39	Male	Architect
44	30-39	Male	Architect
45	30-39	Female	Architect
46	30-39	Female	Other
47	20-29	Female	Civil/Construction Engineer
48	40-49	Male	Architect
49	30-39	Male	Other
50	20-29	Male	Student (in the architectural field)
51	19 and under	Female	Student (in the architectural field)
52	30-39	Male	Other
53	20-29	Male	Interior/Product Designer
54	19 and under	Female	Other
55	20-29	Male	Student (in the architectural field)
56	19 and under	Female	Other
57	20-29	Male	Architectural Assistant
58	19 and under	Female	Student (in the architectural field)
59	19 and under	Female	Student (in the architectural field)
60	30-39	Male	Architect
61	30-39	Male	Architectural Illustrator
62	30-39	Male	Other
63	30-39	Female	Other
64	20-29	Female	Other
65	19 and under	Female	Student (in the architectural field)
66	20-29	Female	Student (in the architectural field)
67	30-39	Male	Developer
68	20-29	Female	Architect
69	30-39	Male	3D Artist
70	20-29	Female	Architect
71	19 and under	Female	Student (in the architectural field)
72	30-39	Male	Other
73	40-49	Male	Other
74	40-49	Male	Interior/Product Designer
75	30-39	Male	Architect
76	20-29	Female	Other
77	30-39	Male	Architect
78	20-29	Female	Architect
79	20-29	Female	Architect
80	20-29	Female	Other
81	40-49	Male	Civil/Construction Engineer

82	20-29	Female	Other
83	20-29	Male	Student (in the architectural field)
84	20-29	Male	Architectural Illustrator
85	30-39	Male	Architect
86	20-29	Male	Student (in the architectural field)
87	30-39	Male	Interior/Product Designer
88	40-49	Male	Architect
89	20-29	Female	Student (in the architectural field)
90	40-49	Male	Architect
91	30-39	Male	Architectural Illustrator
92	20-29	Female	Student (in the architectural field)
93	20-29	Male	Architect
94	20-29	Male	Architectural Assistant
95	19 and under	Male	Student (in the architectural field)
96	30-39	Male	Other
97	19 and under	Female	Other
98	30-39	Female	Other
99	20-29	Female	Other
100	20-29	Male	Architect
101	20-29	Male	Civil/Construction Engineer
102	40-49	Male	Other
103	20-29	Male	Academic (in the architectural field)
104	20-29	Male	Civil/Construction Engineer
105	30-39	Male	Academic (in the architectural field)
106	30-39	Female	Architect
107	20-29	Female	Civil/Construction Engineer
108	40-49	Male	Other
109	40-49	Male	Other
110	20-29	Female	Architectural Assistant
111	20-29	Male	Architect
112	20-29	Male	Architect
113	30-39	Male	3D Artist
114	20-29	Female	Other
115	20-29	Female	Student (in the architectural field)
116	20-29	Female	Student (in the architectural field)
117	30-39	Male	Developer
118	40-49	Female	Other
119	19 and under	Female	Student (in the architectural field)
120	30-39	Male	Architect
121	20-29	Female	Student (in the architectural field)
122	30-39	Male	Other
123	20-29	Female	Student (in the architectural field)
124	20-29	Female	Student (in the architectural field)
125	20-29	Female	Civil/Construction Engineer
126	30-39	Female	Architect
127	30-39	Male	Other
128	30-39	Female	Student (in the architectural field)

129	30-39	Male	Other
130	20-29	Female	Student (in the architectural field)
131	20-29	Male	Interior/Product Designer
132	30-39	Female	Student (in the architectural field)
133	30-39	Male	Other
134	20-29	Male	Architect
135	19 and under	Male	Student (in the architectural field)
136	19 and under	Female	Student (in the architectural field)
137	20-29	Female	Architect
138	20-29	Male	Architect
139	20-29	Male	Student (in the architectural field)
140	30-39	Male	3D Artist
141	30-39	Male	Architect
142	30-39	Male	Architect
143	20-29	Male	Architectural Illustrator
144	30-39	Female	Architect
145	60+	Female	Other
146	20-29	Female	Architectural Assistant
147	30-39	Male	Architectural Illustrator
148	30-39	Female	Architect
149	40-49	Male	Architect
150	30-39	Male	Architect
151	30-39	Male	Other
152	40-49	Male	Other
153	30-39	Female	Other
154	30-39	Female	Other

Section Communication

Detailed percentages of correct and incorrect answers are shown in Tabs 1, 2 and 3 in the following pages

#	Q#4 Pick the image/images which you think represent the building designed by the architect.	Q#5 Pick the image/images which you think represent the building designed by the architect.	Q#6 Pick the image/images which you think represent the building designed by the architect.	Q#7 Pick the image/images which you think represent the building designed by the architect.
1	1	2	1	1
2	1	2	1	2
3	1	2	3	1
4	1	2	3	1
5	1	2	3	1
6	1	2	4	2
7	3	2	3	1
8	1	1	3	2
9	1	1	3	1
10	1	2	3	1
11	1	2	3	1
12	1	2	3	2
13	2	1	4	1
14	1	2	3	1
15	1	2	3	2
16	1	2	4	2
17	1	2	3	1
18	1	2	3	1
19	1	2	1	2
20	1	2	1	2
21	2	2	4	2
22	1	2	3	2
23	1	2	3	1
24	1	2	1	2

25	1	2	3	1
26	1	2	3	2
27	1	2	3	2
28	2	2	3	2
29	1	1	3	1
30	3	2	3	2
31	1	2	1	2
32	1	2	1	1
33	1	2	3	1
34	2	1	4	2
35	1	2	3	2
36	1	1	3	2
37	1	2	3	2
38	1	2	3	2
39	1	2	3	1
40	1	2	3	2
41	1	2	3	2
42	1	2	1	1
43	1	2	3	2
44	1	2	1	2
45	1	2	1	1
46	1	2	3	2
47	1	2	3	2
48	1	2	4	2
49	2	2	4	2
50	1	2	3	2
51	3	2	4	1
52	1	2	3	2
53	1	2	4	2
54	2	2	3	1
55	1	2	3	2
56	1	2	3	1
57	2	2	1	2
58	1	1	3	2
59	1	2	3	1
60	1	2	3	1
61	1	2	3	2
62	1	2	3	1
63	1	2	3	1
64	1	2	3	1
65	1	2	3	2
66	1	2	3	2
67	1	2	3	2
68	1	2	3	1
69	1	2	1	1

70	1	1	3	2
71	1	2	3	2
72	1	2	3	1
73	1	2	4	1
74	1	2	3	2
75	1	2	1	2
76	1	2	3	2
77	1	2	1	2
78	3	2	4	2
79	1	2	3	2
80	1	2	3	2
81	1	2	1	2
82	1	2	3	2
83	1	2	1	1
84	1	2	1	2
85	2	2	3	2
86	1	2	3	2
87	1	2	3	2
88	1	2	3	2
89	1	2	3	2
90	1	2	4	2
91	1	1	3	2
92	1	2	3	1
93	1	1	3	2
94	1	2	3	1
95	1	2	1	2
96	1	1	3	2
97	1	2	3	1
98	1	2	3	1
99	1	2	1	1
100	1	2	3	1
101	1	2	1	2
102	2	1	3	1
103	1	2	4	2
104	1	2	4	2
105	2	2	3	2
106	1	2	1	1
107	2	1	1	2
108	1	2	3	1
109	1	2	3	2
110	1	2	3	1
111	1	2	3	1
112	1	2	1	1
113	1	2	1	2
114	1	2	3	1
115	1	2	1	1
116	1	2	3	2

117	2	2	3	2
118	3	2	3	2
119	1	2	3	2
120	1	2	3	2
121	1	2	3	2
122	1	2	3	2
123	1	2	3	2
124	1	2	3	1
125	1	2	3	1
126	1	2	3	1
127	1	2	1	2
128	1	2	4	2
129	1	2	1	2
130	1	2	3	2
131	1	2	3	1
132	1	2	3	2
133	1	1	4	2
134	1	2	3	2
135	1	2	3	1
136	1	2	1	2
137	1	2	1	2
138	1	2	3	1
139	1	2	3	2
140	1	2	1	2
141	1	2	3	2
142	1	2	3	2
143	1	2	3	2
144	1	2	3	2
145	1	2	3	1
146	1	1	3	2
147	1	2	1	2
148	1	2	4	2
149	1	2	3	1
150	1	2	3	2
151	1	2	3	1
152	1	2	4	2
153	1	2	3	1
154	1	2	1	2

Section Recognisability

Detailed percentages of correct and incorrect answers are shown in Tabs 1, 2 and 3 in the

#	Q#8 Using the previous set of images as a reference, assign each illustration to the correct architect.	Q#9 Using the previous set of images as a reference, assign each render to the correct architect.
1	1.Piano - 2.Sekkei - 3.Foster	1.Piano - 2.Sekkei - 3.Foster
2	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
3	1.Piano - 2.Sekkei - 3.Foster	1.Piano - 2.Sekkei - 3.Foster
4	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
5	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Sekkei - 3.Foster
6	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
7	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
8	1.Sekkei - 2.Piano - 3.Foster	1.Foster - 2.Sekkei - 3.Piano
9	1.Foster - 2.Sekkei - 3.Piano	1.Foster - 2.Piano - 3.Sekkei
10	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Sekkei - 3.Piano
11	1.Piano - 2.Sekkei - 3.Foster	1.Piano - 2.Foster - 3.Sekkei
12	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
13	1.Piano - 2.Foster - 3.Sekkei	1.Piano - 2.Foster - 3.Sekkei
14	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
15	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Sekkei - 3.Foster
16	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Sekkei - 3.Piano
17	1.Foster - 2.Sekkei - 3.Piano	1.Piano - 2.Sekkei - 3.Foster
18	1.Piano - 2.Sekkei - 3.Foster	1.Piano - 2.Sekkei - 3.Foster
19	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei- 2.Piano - 3.Foster
20	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
21	1.Foster - 2.Sekkei - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
22	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
23	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Sekkei - 3.Foster
24	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Sekkei - 3.Piano
25	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Sekkei - 3.Piano
26	1.Foster - 2.Sekkei - 3.Piano	1.Foster - 2.Sekkei - 3.Piano
27	1.Sekkei - 2.Piano - 3.Foster	1.Sekkei- 2.Piano - 3.Foster
28	1.Piano - 2.Foster - 3.Sekkei	1.Foster - 2.Sekkei - 3.Piano
29	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
30	1.Foster - 2.Piano - 3.Sekkei	1.Foster - 2.Sekkei - 3.Piano

31	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Sekkei - 3.Piano
32	1.Sekkei - 2.Piano - 3.Foster	1.Foster - 2.Piano - 3.Sekkei
33	1.Foster - 2.Piano - 3.Sekkei	1.Foster - 2.Piano - 3.Sekkei
34	1.Foster - 2.Piano - 3.Sekkei	1.Foster - 2.Piano - 3.Sekkei
35	1.Foster - 2.Piano - 3.Sekkei	1.Foster - 2.Piano - 3.Sekkei
36	1.Piano - 2.Foster - 3.Sekkei	1.Foster - 2.Sekkei - 3.Piano
37	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Sekkei - 3.Foster
38	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
39	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
40	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Sekkei - 3.Foster
41	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
42	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
43	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
44	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
45	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Sekkei - 3.Foster
46	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
47	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
48	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
49	1.Foster - 2.Sekkei - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
50	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
51	1.Piano - 2.Sekkei - 3.Foster	1.Piano - 2.Sekkei - 3.Foster
52	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei- 2.Piano - 3.Foster
53	1.Piano - 2.Foster - 3.Sekkei	1.Foster - 2.Sekkei - 3.Piano
54	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
55	1.Foster - 2.Piano - 3.Sekkei	1.Sekkei- 2.Piano - 3.Foster
56	1.Piano - 2.Foster - 3.Sekkei	1.Piano - 2.Foster - 3.Sekkei
57	1.Piano - 2.Foster - 3.Sekkei	1.Piano - 2.Sekkei - 3.Foster
58	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Sekkei - 3.Foster
59	1.Foster - 2.Sekkei - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
60	1.Piano - 2.Sekkei - 3.Foster	1.Piano - 2.Sekkei - 3.Foster
61	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Sekkei - 3.Piano
62	1.Piano - 2.Foster - 3.Sekkei	1.Foster - 2.Piano - 3.Sekkei
63	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Sekkei - 3.Piano
64	1.Piano - 2.Foster - 3.Sekkei	1.Sekkei - 2.Foster - 3.Piano
65	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
66	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Sekkei - 3.Foster
67	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
68	1.Piano - 2.Foster - 3.Sekkei	1.Sekkei - 2.Foster - 3.Piano
69	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Sekkei - 3.Foster
70	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Sekkei - 3.Piano
71	1.Foster - 2.Piano - 3.Sekkei	1.Piano - 2.Foster - 3.Sekkei
72	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
73	1.Piano - 2.Sekkei - 3.Foster	1.Foster - 2.Sekkei - 3.Piano
74	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Sekkei - 3.Piano
75	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano

76	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Sekkei - 3.Piano
77	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
78	1.Piano - 2.Foster - 3.Sekkei	1.Sekkei - 2.Foster - 3.Piano
79	1.Sekkei - 2.Piano - 3.Foster	1.Piano - 2.Foster - 3.Sekkei
80	1.Sekkei - 2.Piano - 3.Foster	1.Piano - 2.Foster - 3.Sekkei
81	1.Foster - 2.Sekkei - 3.Piano	1.Piano - 2.Sekkei - 3.Foster
82	1.Piano - 2.Foster - 3.Sekkei	1.Foster - 2.Sekkei - 3.Piano
83	1.Sekkei - 2.Piano - 3.Foster	1.Piano - 2.Sekkei - 3.Foster
84	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Sekkei - 3.Piano
85	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
86	1.Foster - 2.Piano - 3.Sekkei	1.Piano - 2.Foster - 3.Sekkei
87	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei- 2.Piano - 3.Foster
88	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Sekkei - 3.Foster
89	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
90	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Piano - 3.Sekkei
91	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Sekkei - 3.Foster
92	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
93	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
94	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Sekkei - 3.Piano
95	1.Sekkei - 2.Piano - 3.Foster	1.Sekkei- 2.Piano - 3.Foster
96	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
97	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
98	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
99	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
100	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Piano - 3.Sekkei
101	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
102	1.Sekkei - 2.Piano - 3.Foster	1.Sekkei - 2.Foster - 3.Piano
103	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Sekkei - 3.Piano
104	1.Sekkei - 2.Piano - 3.Foster	1.Foster - 2.Sekkei - 3.Piano
105	1.Foster - 2.Sekkei - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
106	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
107	1.Sekkei - 2.Piano - 3.Foster	1.Piano - 2.Sekkei - 3.Foster
108	1.Sekkei - 2.Piano - 3.Foster	1.Foster - 2.Sekkei - 3.Piano
109	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
110	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
111	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Piano - 3.Sekkei
112	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Sekkei - 3.Piano
113	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Sekkei - 3.Foster
114	1.Piano - 2.Foster - 3.Sekkei	1.Sekkei- 2.Piano - 3.Foster
115	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
116	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
117	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
118	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
119	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Sekkei - 3.Foster
120	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Piano - 3.Sekkei
121	1.Piano - 2.Foster - 3.Sekkei	1.Piano - 2.Foster - 3.Sekkei
122	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Piano - 3.Sekkei

123	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Piano - 3.Sekkei
124	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
125	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
126	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
127	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Sekkei - 3.Piano
128	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Sekkei - 3.Piano
129	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Sekkei - 3.Foster
130	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Sekkei - 3.Piano
131	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
132	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
133	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei- 2.Piano - 3.Foster
134	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Piano - 3.Sekkei
135	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Piano - 3.Sekkei
136	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
137	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
138	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Sekkei - 3.Foster
139	1.Foster - 2.Sekkei - 3.Piano	1.Foster - 2.Sekkei - 3.Piano
140	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
141	1.Foster - 2.Sekkei - 3.Piano	1.Foster - 2.Sekkei - 3.Piano
142	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Sekkei - 3.Piano
143	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Sekkei - 3.Foster
144	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
145	1.Sekkei - 2.Foster - 3.Piano	1.Sekkei - 2.Foster - 3.Piano
146	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Sekkei - 3.Piano
147	1.Piano - 2.Foster - 3.Sekkei	1.Piano - 2.Foster - 3.Sekkei
148	1.Piano - 2.Foster - 3.Sekkei	1.Piano - 2.Sekkei - 3.Foster
149	1.Piano - 2.Foster - 3.Sekkei	1.Foster - 2.Sekkei - 3.Piano
150	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Foster - 3.Sekkei
151	1.Sekkei - 2.Foster - 3.Piano	1.Piano - 2.Sekkei - 3.Foster
152	1.Piano - 2.Foster - 3.Sekkei	1.Foster - 2.Piano - 3.Sekkei
153	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Sekkei - 3.Piano
154	1.Sekkei - 2.Foster - 3.Piano	1.Foster - 2.Piano - 3.Sekkei

Section Engagement

Detailed percentages of correct and incorrect answers are shown in Tabs 1, 2 and 3 in the following pages

#	This living room is represented with an illustration and a render. Mark which image you prefer.	This bedroom is represented with an illustration and a render. Mark which image you prefer.
1	illustration	Render
2	illustration	Render
3	render	Illustration
4	illustration	Render
5	illustration	Render
6	render	Render
7	render	Render
8	render	Render
9	render	Render
10	illustration	Render
11	illustration	Render
12	render	Render
13	render	Render
14	render	Illustration
15	illustration	Render
16	illustration	Illustration
17	render	Render
18	render	Render
19	render	Render
20	illustration	Illustration
21	illustration	Illustration
22	illustration	Render
23	render	Render
24	render	Illustration
25	render	Illustration
26	illustration	Illustration
27	illustration	Illustration
28	render	Illustration
29	illustration	Illustration
30	render	Render
31	illustration	Render
32	illustration	Illustration

33	render	Render
34	illustration	Illustration
35	illustration	Illustration
36	render	Illustration
37	illustration	Illustration
38	illustration	Illustration
39	illustration	Illustration
40	render	Render
41	illustration	Render
42	render	Render
43	render	Render
44	render	Render
45	illustration	Render
46	render	Render
47	render	Render
48	illustration	Illustration
49	illustration	Illustration
50	illustration	Illustration
51	render	Render
52	render	Render
53	render	Render
54	illustration	Render
55	illustration	Render
56	render	Illustration
57	illustration	Illustration
58	illustration	Illustration
59	render	Render
60	illustration	Render
61	illustration	Illustration
62	illustration	illustration
63	illustration	render
64	illustration	render
65	render	render
66	render	render
67	render	render
68	illustration	illustration
69	illustration	render
70	render	illustration
71	render	render
72	render	render
73	render	render
74	render	render
75	render	render
76	illustration	illustration
77	illustration	render

78	illustration	render
79	illustration	illustration
80	render	render
81	render	illustration
82	illustration	illustration
83	illustration	illustration
84	illustration	illustration
85	render	render
86	illustration	illustration
87	illustration	render
88	illustration	render
89	render	render
90	illustration	render
91	render	illustration
92	render	render
93	illustration	render
94	illustration	illustration
95	render	render
96	render	illustration
97	illustration	illustration
98	render	illustration
99	illustration	illustration
100	illustration	render
101	illustration	illustration
102	illustration	illustration
103	illustration	render
104	render	render
105	illustration	illustration
106	illustration	illustration
107	illustration	illustration
108	illustration	illustration
109	render	illustration
110	illustration	illustration
111	illustration	render
112	illustration	illustration
113	illustration	illustration
114	illustration	illustration
115	illustration	illustration
116	illustration	illustration
117	render	illustration
118	illustration	render
119	illustration	illustration
120	render	render
121	render	render
122	render	render
123	render	render
124	render	render

125	render	render
126	render	render
127	illustration	render
128	illustration	illustration
129	illustration	illustration
130	illustration	illustration
131	render	illustration
132	render	render
133	render	render
134	render	render
135	illustration	illustration
136	illustration	illustration
137	illustration	render
138	illustration	illustration
139	render	render
140	render	render
141	illustration	render
142	illustration	illustration
143	illustration	illustration
144	illustration	illustration
145	render	render
146	render	render
147	render	illustration
148	illustration	illustration
149	illustration	illustration
150	render	render
151	illustration	illustration
152	render	render
153	render	render
154	illustration	render

TAB1 - GENERAL

154 responses

Question n°	Most popular answer (Mode)	Least popular answer	Correct Answers
Personal Details			
1 Age	39% 20-29 1%	50-59	
2 Gender	58% M	42% F	
3 Occupation	29% Architect	0% Real Estate Agent	
Communication			
4 Illustration - Which building is the project			
	87% Correct	0% Incorrect	87%
5 Illustration - Which building is the project			
	89% Correct	10% Incorrect	89%
6 Render - Which building is the project			
	66% Incorrect	0% Incorrect	20%
7 Render - Which building is the project			
	62% Correct	37% Incorrect	62%
Recognizability			
8 Illustration - Link the image to the correct architect			
	65% Correct	4% Incorrect	65%
9 Render - Link the image to the correct architect			
	25% Incorrect	5% Incorrect	21%
Engagement			
10 Pick the preferred image			
	54% Illustration	45% Render	
11 Pick the preferred image			
	52% Render	47% Illustration	
Non compulsory questions - architectural field			
12 Course for drawing with digital tabets			
	73% Yes	26% No	
13 Use of renders			
	72% Final Presentation	5% Never	
14 Use of illustrations			

81% Concept 1% Never

TAB2 - PROFESSIONALS IN THE ARCHITECTURAL FIELD

115 responses

Question n°	Most popular answer (Mode)	Least popular answer	Correct Answers
Personal Details			
Communication			
4 Illustration	89% Correct	0%	Incorrect 89%
5 Illustration	93% Correct	7%	Incorrect 93%
6 Render	65% Incorrect	0%	Incorrect 23%
7 Render	67% Correct	33%	Incorrect 19%
Recognizability			
8 Illustration	70% Correct	3%	Incorrect 70%
9 Render	27% Incorrect	4%	Incorrect 21%
Engagement			
10	56% Illustration	44% Render	
11	56% Render	44% Illustration	

Non compulsory questions - architectural field

12 Course for drawing with digital tabets 77% Yes 23% No

13 Use of renders 69% Final Presentation 4% Never

14 Use of illustrations 79% Concept 1% Never

TAB3 - OTHERS

39 responses

Question n°	Most popular answer (Mode)	Least popular answer	Correct Answers
Communication			
4 Illustration	87% Correct	0%Incorrect	87%
5 Illustration	82% Correct	18% Incorrect	82%
6 Render	74% Incorrect	0% Incorrect	13%
7 Render	51% Correct	49% Incorrect	51%
Recognizability			
8 Illustration	56% Correct	5% Incorrect	56%
9 Render	23% Correct/Incorrect	8% Incorrect	23%

Engagement

10 Pick the preferred image 51% Illustration 49% Render

11 Pick the preferred image 51% Illustration 49% Render

Non compulsory questions - architectural field

12 Course for drawing with digital tabets 64% Yes 36% No

13 Use of renders n.a.

14 Use of illustrations   n.a.

ANNEX 2

Annex 2: Neurophysiological experiments of Part 3

Experiment 1

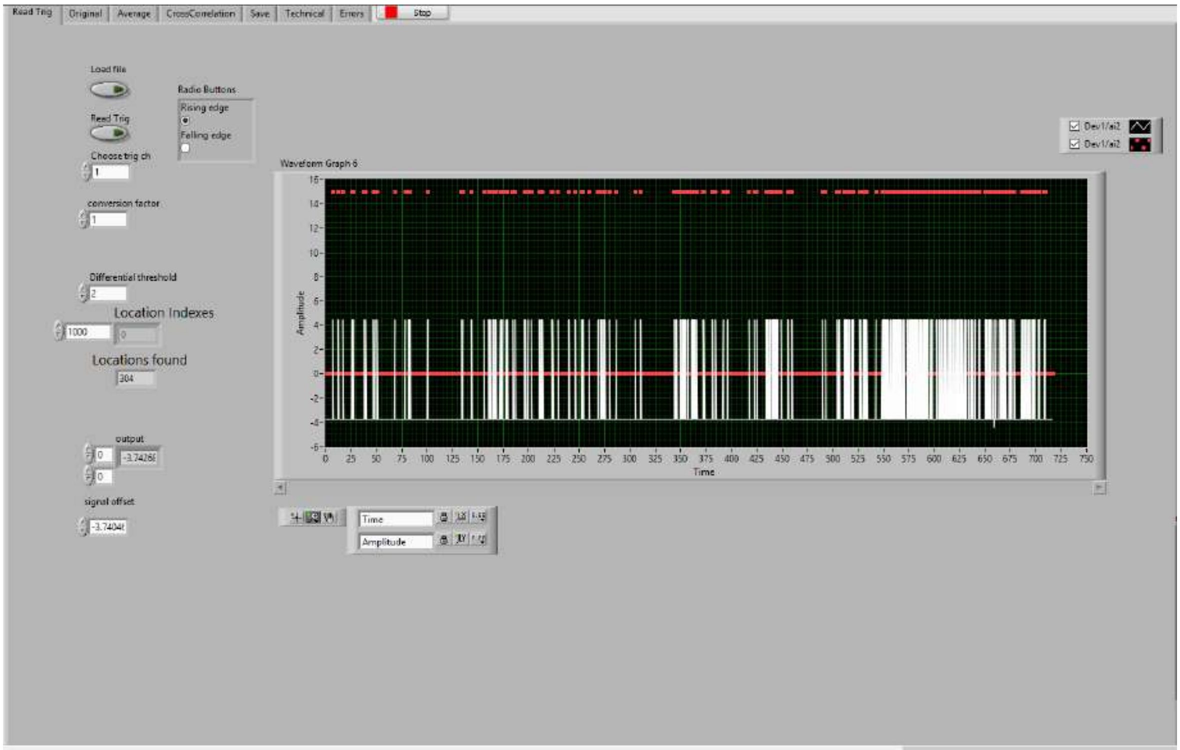
Experiment 2

Experiment 3

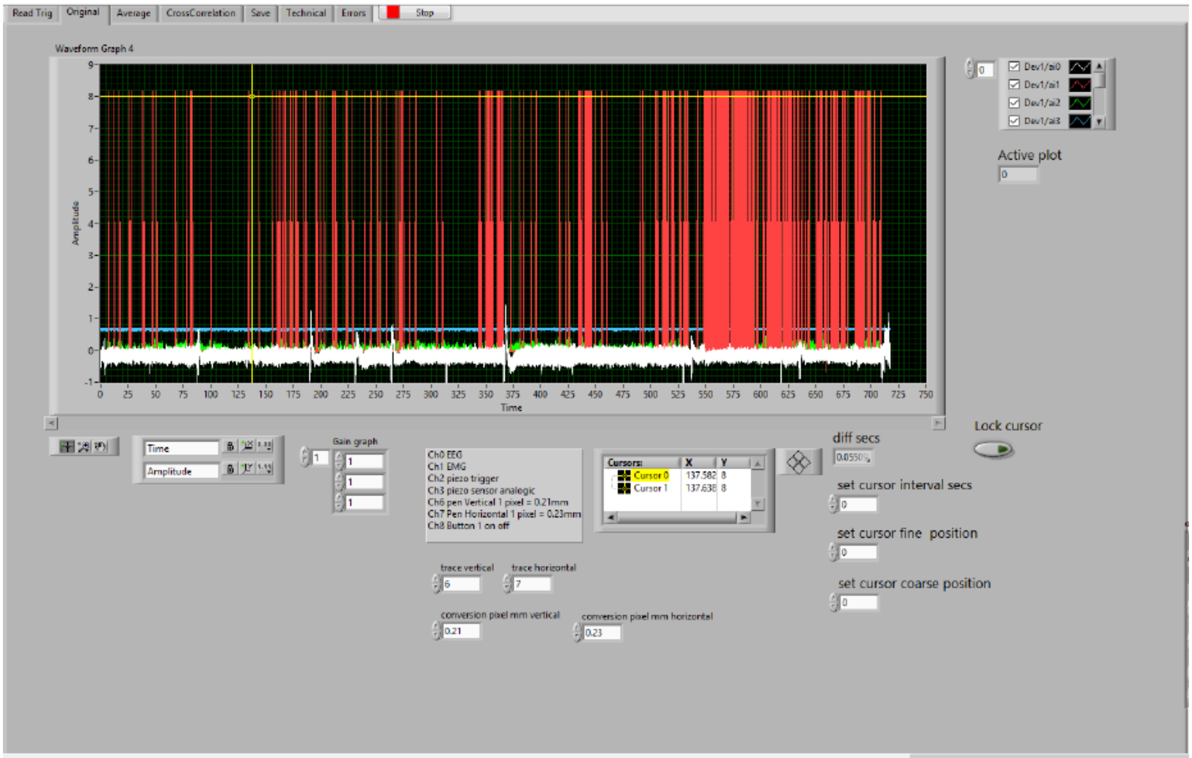
Experiment 1

Recording and analysis of EEG signals during freehand drawing on digital tablet on 9 subjects

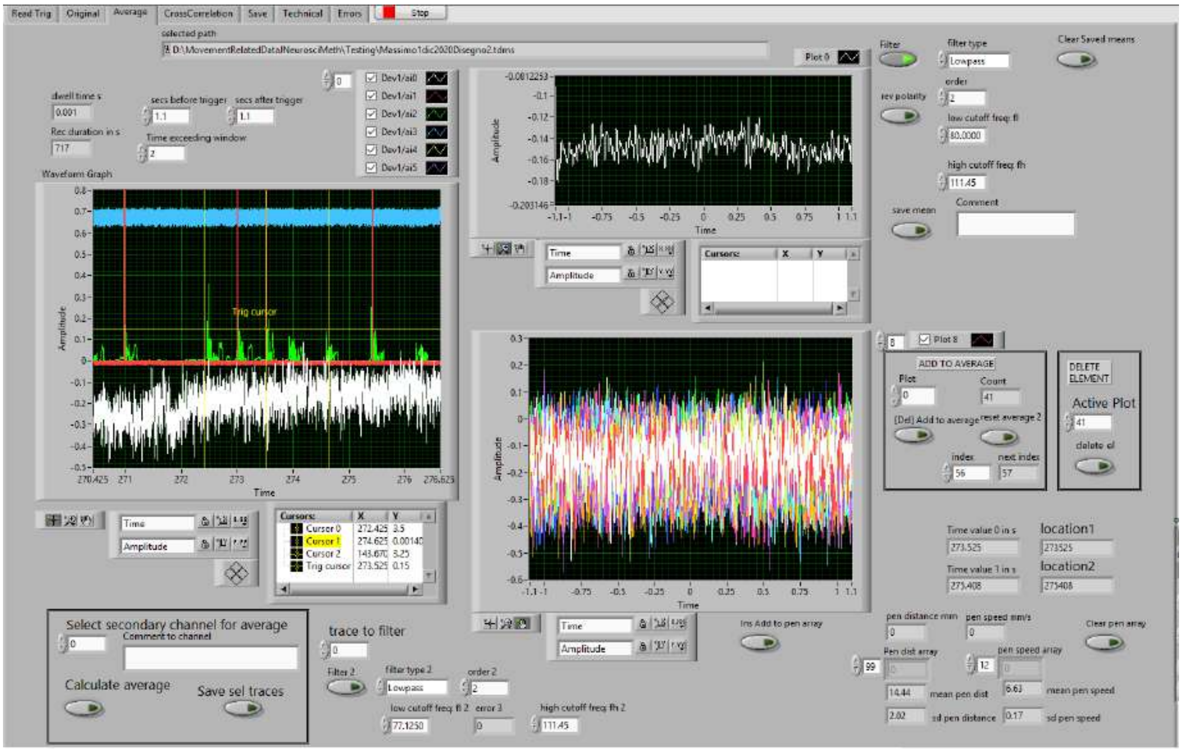
Software for reading raw data.



First screen of the reading software. The software had to be especially written for these experiments. A recorded file is retrieved for analysis with the control ‘Load file’. The software identifies the trigger signals produced by the piezoelectric sensors (white trace) and records their position in the time domain building up an index (red dots). In this case 304 triggers have been identified. The recording duration was 720 seconds.



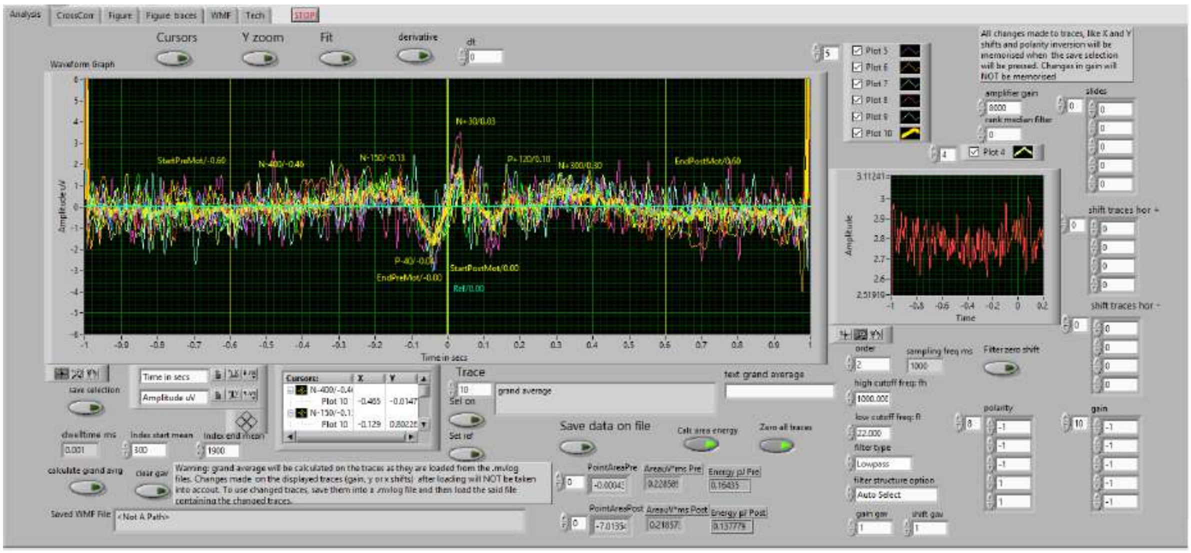
This screen shows the entire recording with all channels. The list of channels and their content is shown just below the graph.



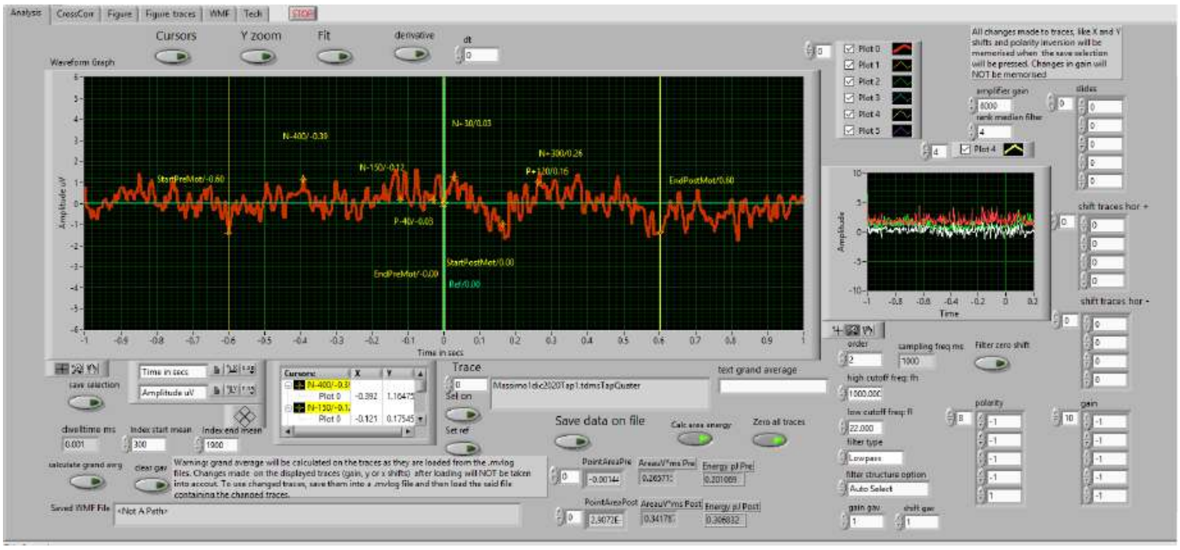
The third screen is where the time epoch before and after the trigger signal is inspected in the left hand graph. If the EEG signal (white trace) is devoid of interference from artefacts, it is accepted for averaging. The analysed epoch is defined by the two yellow vertical lines. The third line in the middle is the time of the reference trigger. The whole recording is thus streamed in the graph while the resulting average is built up and shown in the upper graph on the right (in this case an average of 41 movements is shown). The lower right graph shows all single epochs chosen for average and allows deleting if an interfered trace has been inadvertently sent to average. The resulting average is stored in a new file for further analysis and comparison with other averages.

Software for analysis and comparison of averaged data

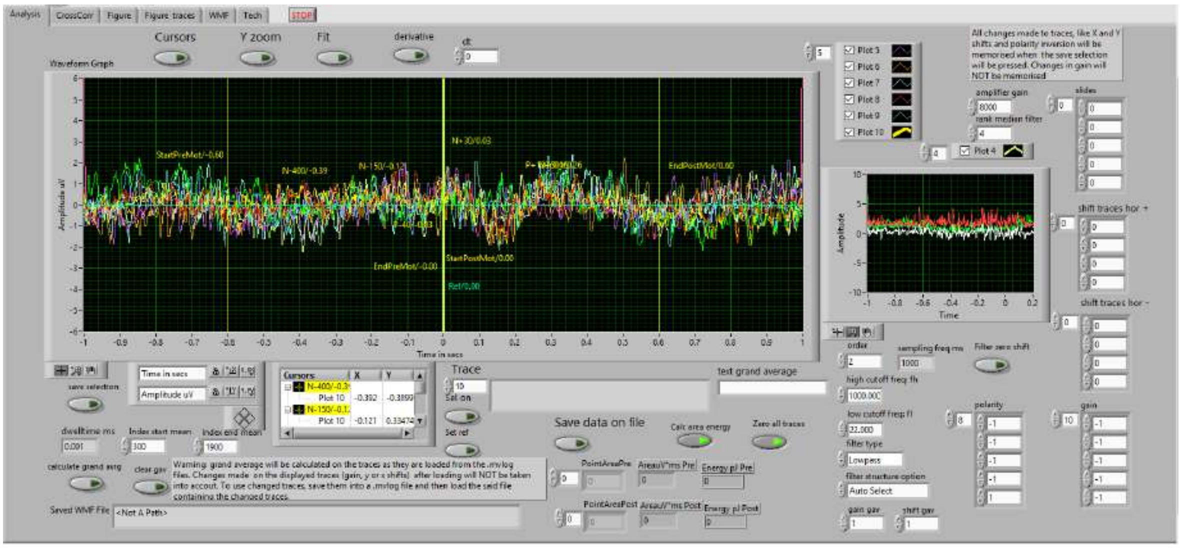
This software allows loading of a number of averaged traces, their comparison, and calculation of the grand average. If necessary, software filtering can be applied. Cursor can be placed on any trace to calculate latency and amplitude of peaks. Also area and energy of the signal can be calculated. With the button ‘Save data on file’ all calculations are transferred onto a spreadsheet file.



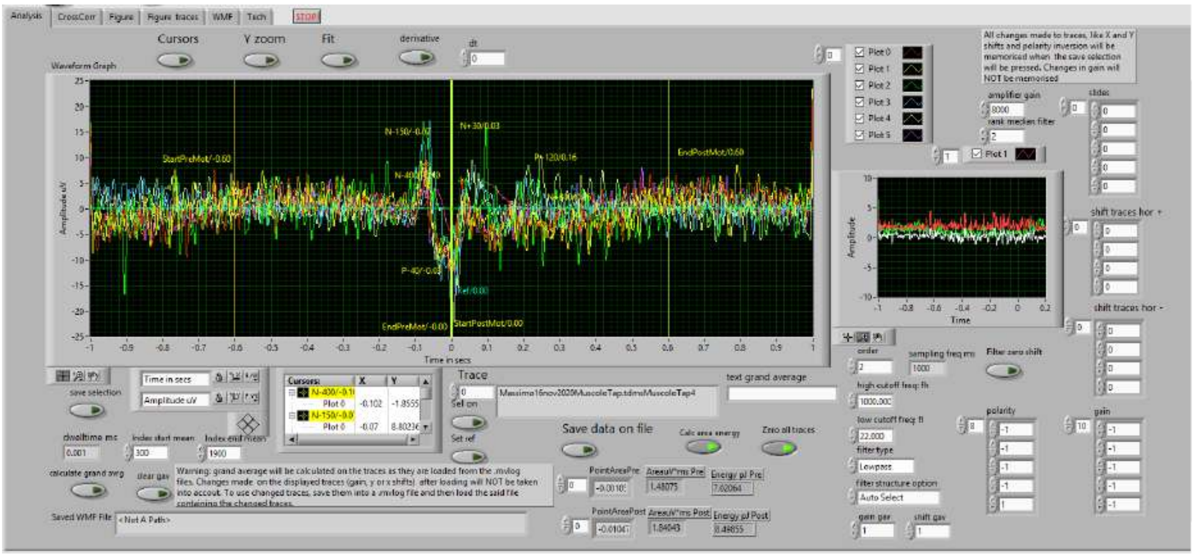
In the graph shown, the single averages of freehand drawing sessions are reported as superimposed traces, with the grand average as the yellow thick trace. Time baseline is in seconds and amplitude in microvolt.



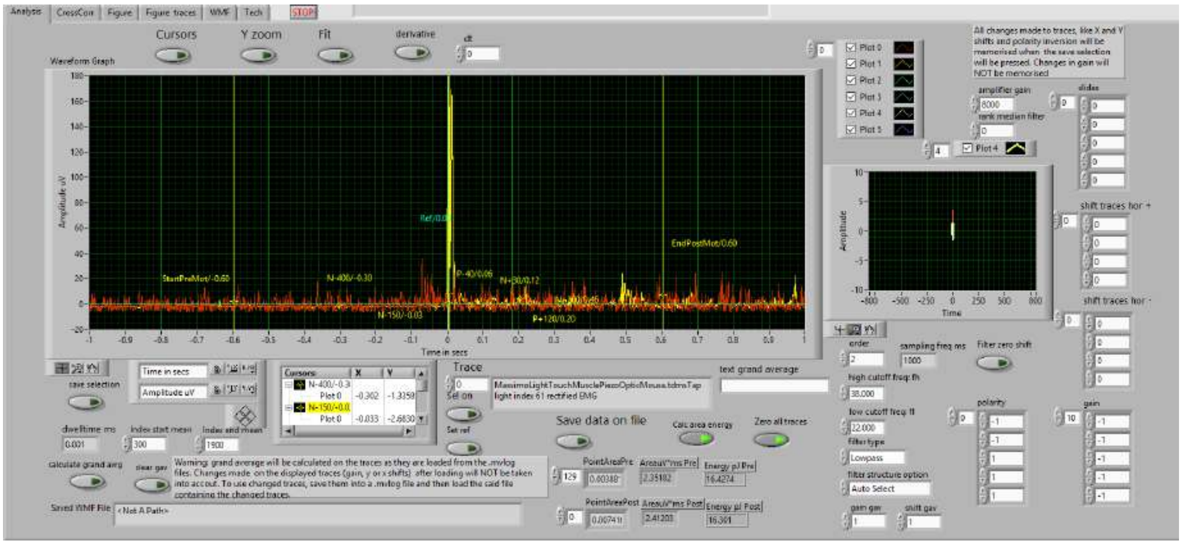
This is the analysis of one single tap averaging, with the detected values.



This graph shows the 9 sessions of pen tapping. The grand average was also calculated and is shown as the yellow thick trace, but it is hardly visible here because of its low amplitude.



The graph shows the recordings of the electromyograms from the 9 sessions.



Electromyograms were also rectified to better identify the onset and peak timings.

Spreadsheet of latency of components in milliseconds

	Subj	Lat0secs	Lat1secs	Lat2secs	Lat3secs	Lat4secs
FreeDraw	1	-144	-41	35	125	213
FreeDraw	2	-181	-36	64	141	226
FreeDraw	3	-166	-44	27	133	182
FreeDraw	4	-152	-39	36	113	211
FreeDraw	5	-141	-39	25	83	166
FreeDraw	6	-145	-43	25	125	185
FreeDraw	7	-130	-43	25	108	174
FreeDraw	8	-126	-52	18	128	181
FreeDraw	9	-146	-47	27	128	181
mean		-147.889	-42.6667	31.33333	120.4444	191
SD		17.01062	4.769696	13.40709	17.13265	20.43282
Grand Average		-0.14082	-0.04382	0.026181	0.123181	0.180181

	Subj	Lat0secs	Lat1secs	Lat2secs	Lat3secs	Lat4secs
Sing Tap	1	-133	-51	31	160	278
Sing Tap	2	-143	-41	24	163	273
Sing Tap	3	-192	-107	40	90	161
Sing Tap	4	-210	-81	19	82	159
Sing Tap	5	-136	-54	91	120	161
Sing Tap	6	-118	-59	9	124	175
Sing Tap	7	-153	-20	39	141	276
Sing Tap	8	-187	-48	90	150	277
Sing Tap	9	-119	-70	32	146	295
media		-154.556	-59	41.66667	130.6667	228.3333
SD		33.67904	24.90984	29.32576	29.15905	61.50813
Grand average		-0.134	-0.055	0.02	0.14	0.284
diff		6.666667	16.33333	-10.3333	-10.2222	-37.3333
T test		0.603345	0.071266	0.350664	0.377984	0.103228

r perc

		onset	N	P	N	P
		Lat0secs	Lat1secs	Lat2secs	Lat3secs	Lat4secs
Muscle	1	-117	-77	-28	42	128
Muscle	2	-126	-72	-28	42	141

Muscle	3	-126	-75	-3	59	150
Muscle	4	-122	-75	-3	59	136
Muscle	5	-114	-78	0	40	122
Muscle	6	-114	-78	-2	33	122
Muscle	7	-101	-57	-7	85	152
Muscle	8	-112	-45	18	97	199
Muscle	9	-123	-76	2	83	129
mean		-117.222	-70.3333	-5.66667	60	142.1111
SD		8.074308	11.51086	14.48275	23.18944	24.01793
diff muscle N-150		30.66667				
		0.000165				

Spreadsheet on amplitude of components in microvolt

	Subj	Ampl0uV	Ampl1uV	Ampl2uV	Ampl3uV	Ampl4uV
FreeDraw	1	1.011309	-2.47443	1.774413	-0.67485	0.483613
FreeDraw	2	1.686247	-2.33785	1.184808	-0.76067	0.158676
FreeDraw	3	1.759789	-2.00563	0.381733	-0.73961	0.712078
FreeDraw	4	1.371046	-3.04747	1.792579	-0.54513	0.938582
FreeDraw	5	0.631132	-1.57219	0.982822	-0.89047	1.024541
FreeDraw	6	0.782911	-1.96009	1.939554	-1.58696	0.49138
FreeDraw	7	0.670044	-2.83826	2.633872	-1.91835	-0.14655
FreeDraw	8	1.109086	-1.6463	0.948757	-1.10108	0.368861
FreeDraw	9	0.28865	-2.64825	3.591097	-2.27495	0.533307
mean		1.034468	-2.28116	1.692182	-1.16579	0.507165
SD		0.49816	0.519326	0.974761	0.615014	0.364896
Grand Average		0.8739	-2.17201	1.524217	-1.00408	0.429028

	Subj	Ampl0uV	Ampl1uV	Ampl2uV	Ampl3uV	Ampl4uV
Sing Tap	1	1.074215	0.189465	0.98669	-2.02582	0.763555
Sing Tap	2	1.066785	0.107427	1.069937	-2.24869	1.066309
Sing Tap	3	0.668856	-0.76422	0.328798	-0.33055	0.579933
Sing Tap	4	0.856126	-0.8734	0.816689	-0.63601	0.802727
Sing Tap	5	0.858184	-0.8381	1.195726	-1.20892	-0.18023
Sing Tap	6	0.838586	-1.02252	1.22835	-1.77143	-0.94752
Sing Tap	7	0.38507	-0.33768	1.139573	-1.5083	1.453318
Sing Tap	8	0.734359	-0.33333	1.189527	-1.98272	1.86153
Sing Tap	9	0.895163	-0.02651	1.211208	-2.42968	-0.6196
media		0.819705	-0.43321	1.0185	-1.57135	0.531113
SD		0.210246	0.458131	0.29081	0.721206	0.93899
Grand average		0.463505	-0.18522	0.822566	-1.16789	1.056157
diff		0.214763	-1.84796	0.673682	0.405561	-0.02395
T test		0.250808	5.5E-07	0.064341	0.217544	0.94403
r perc			81.00937	39.81144		

		Ampl0uV	Ampl1uV	Ampl2uV	Ampl3uV	Ampl4uV
Muscle	1	-2.56712	9.376844	-17.6932	-2.85832	-11.7042
Muscle	2	1.586972	21.8396	-12.1069	-0.32055	-9.23885
Muscle	3	-0.54233	19.45746	-20.7767	10.63273	-4.26786
Muscle	4	-0.94467	12.23416	-19.7693	12.43207	-2.39098
Muscle	5	0.714079	11.39308	-12.8952	4.880064	-4.29935
Muscle	6	3.288352	12.17172	-12.0655	3.987284	-5.71833
Muscle	7	-1.16452	9.707077	-10.7172	6.330579	-1.82705

Muscle	8	-1.00745	4.810547	-10.3939	7.476241	-0.73116
Muscle	9	0.94127	11.64986	-13.6674	3.425479	-2.85448
mean		0.033842	12.51559	-14.4539	5.109508	-4.78136
SD		1.762989	5.177364	3.927978	4.852037	3.600833

Spreadsheet on energy of signal in picoJoule

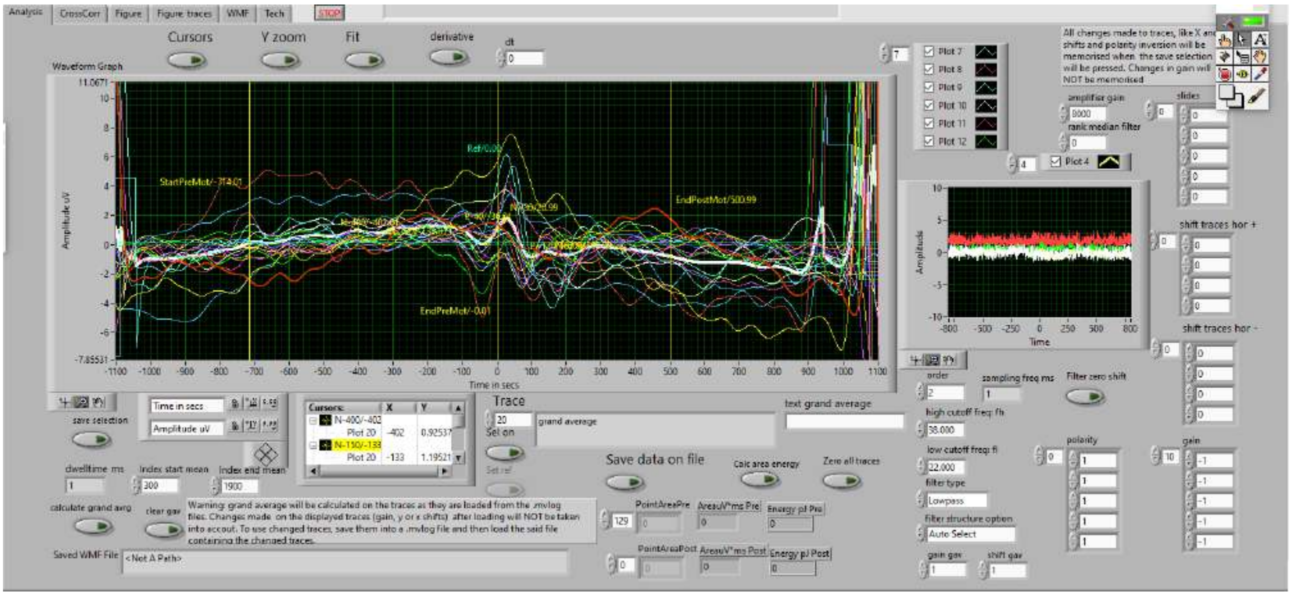
	Subj	Enpre	Enpost	EnTot
FreeDraw	1	383.763	133.7097	517.4727
FreeDraw	2	472.2036	98.49226	570.6959
FreeDraw	3	384.1973	42.64874	426.846
FreeDraw	4	507.5271	144.6407	652.1678
FreeDraw	5	143.0973	91.6376	234.7349
FreeDraw	6	196.4295	251.879	448.3085
FreeDraw	7	348.8134	413.6939	762.5073
FreeDraw	8	149.7998	73.72025	223.5201
FreeDraw	9	347.3334	719.5275	1066.861
Mean		325.9071	218.8833	544.7904
SD		133.8446	219.4503	263.5038
Grand Average		262.8967	113.251	376.1477

	Subj	Enpre	Enpost	EnTot
Sing Tap	1	67.41533	269.3925	336.8079
Sing Tap	2	72.787	322.009	394.796
Sing Tap	3	33.40475	17.56146	50.96621
Sing Tap	4	57.19504	56.31065	113.5057
Sing Tap	5	73.93448	107.047	180.9815
Sing Tap	6	84.22169	240.6125	324.8342
Sing Tap	7	16.67368	158.125	174.7987
Sing Tap	8	24.30505	186.4874	210.7925
Sing Tap	9	70.23802	451.3117	521.5497
Mean		55.575	200.9841	256.5591
SD		24.48066	136.4764	149.0196
Grand average		23.55956	111.9574	135.517
diff		270.3321	17.89916	288.2313
T test		2E-05	0.838018	0.011429
r perc		82.9476		52.90682

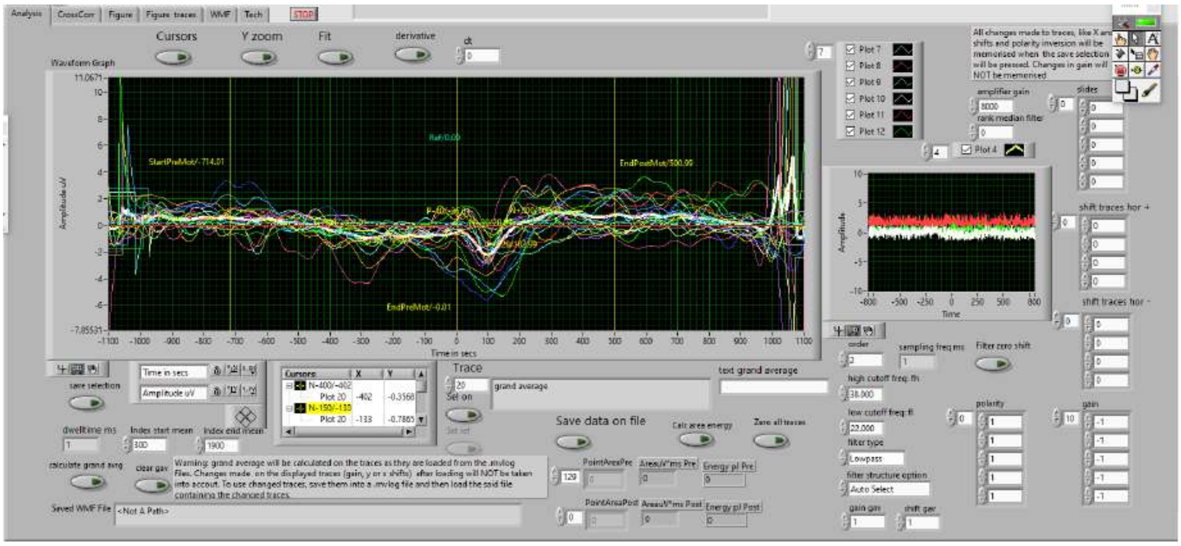
		Enpre	Enpost	EnTot
Muscle	1	15660.75	17445.44	33106.19
Muscle	2	18365.17	5850.874	24216.04
Muscle	3	26154.06	11393.79	37547.84
Muscle	4	13816.14	16687.94	30504.08

Muscle	5	9740.56	3489.468	13230.03
Muscle	6	9943.526	3105.028	13048.55
Muscle	7	4741.943	2735.763	7477.706
Muscle	8	1343.259	6395.352	7738.611
Muscle	9	8783.872	3706.739	12490.61
mean		12061.03	7867.822	19928.85
SD		7445.147	5849.154	11540.47

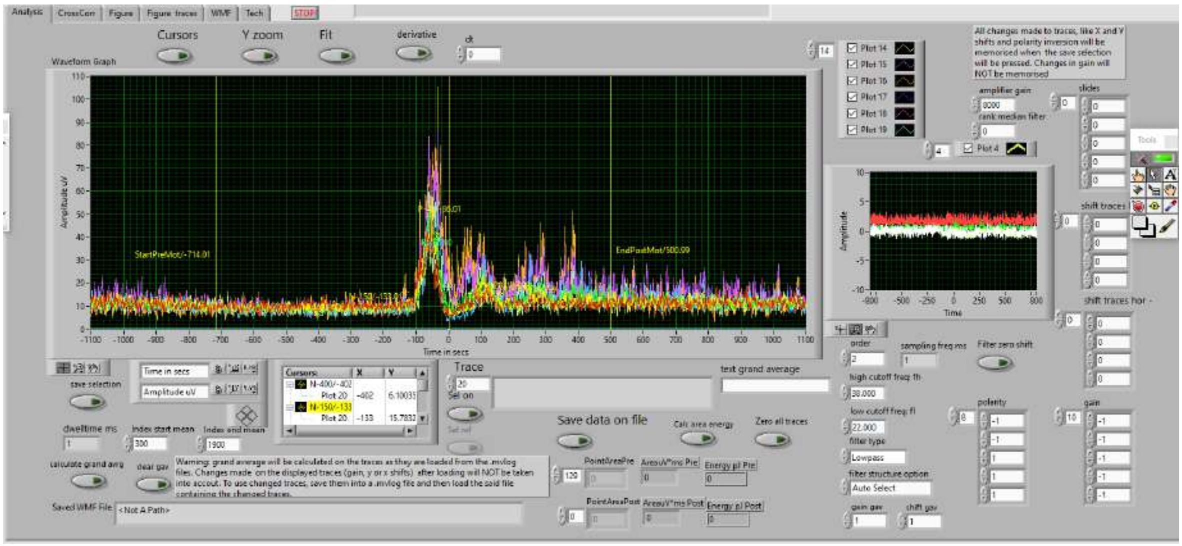
Experiment 2



Recordings during freehand drawing. Single averaged traces of the 20 subjects, and grand average (white thick trace)



Recordings during CAD drawing with mouse. Single averages and grand average.



Recordings of rectified muscle electromyogram

Single averages of the 20 subjects during freehand drawing. Latencies of components of MRPs in milliseconds.

Subj	N-400 ms	N-150 ms	P-40 ms	N+40 ms	P+120 ms	N+300 ms
1	-397	-204	-91	-21	150	456
2	-414	-97	-42	42	150	456
3	-445	-215	-24	39	93	265
4	-418	-121	-42	35	101	306
5	-438	-108	-9	29	110	262
6	-423	-112	-24	22	101	348
7	-420	-91	-30	30	101	348
8	-494	-150	-42	51	181	283
9	-400	-109	-57	35	177	343
10	-377	-175	-82	30	156	251
11	-422	-181	-26	26	107	350
12	-420	-256	-46	26	96	269
13	-359	-132	-46	37	109	310
14	-377	-116	-53	8	71	350
15	-388	-143	-48	15	71	375
16	-307	-98	-33	28	80	402
17	-429	-107	-42	24	71	393
18	-402	-172	-46	24	80	433
19	-406	-161	-51	24	129	438
20	-528	-152	-37	19	172	339
Mean	-413.2	-145	-43.55	26.15	115.3	348.85
Sd	45.85974	44.82363	18.78822	14.70508	36.69949	65.61071

Single averages during CAD drawing. Latencies of components

Subj	N-400 ms	N-150 ms	P-40 ms	N+40 ms	P+120 ms	N+300 ms
1	-415	-175	-39	30	84	339
2	-445	-235	-17	44	118	217
3	-445	-220	-53	37	107	274
4	-445	-134	-15	24	118	395
5	-402	-109	-66	35	105	395
6	-368	-120	-57	6	87	325
7	-350	-132	-48	21	107	303
8	-440	-111	-26	28	105	294
9	-413	-80	-44	21	78	294
10	-458	-98	-44	17	84	370
11	-413	-168	-51	17	53	319
12	-382	-197	-44	24	93	368
13	-352	-154	-71	10	80	391
14	-456	-111	-60	17	102	238
15	-463	-215	-21	69	132	276
16	-463	-64	-10	69	125	289
17	-528	-211	3	10	102	411
18	-413	-118	-21	15	87	384
19	-359	-190	-3	48	132	328
20	-384	-154	-82	12	136	395
mean	-419.7	-149.8	-38.45	27.7	101.75	330.25
Sd	45.63021	49.78226	23.6587	18.0645	21.40309	56.8626

Single averages during freehand drawing, amplitude of components in microvolts.

DRAW	Amplitude								
Subj	N-400 uV	N-150 uV	P-40 uV	N-150-P-40	N+40 uV	P-40-N+40	P+120 uV	N+300 uV	P+120-N+300
1	-0.1	2.2	1.0	1.2	1.5	0.5	-1.0	2.4	3.4
2	0.5	5.1	4.6	0.5	7.5	2.9	3.0	-3.0	6.1
3	2.2	1.3	1.2	0.1	3.4	2.2	1.6	2.0	0.4
4	0.7	1.4	-1.2	2.6	0.3	1.5	-1.4	1.5	3.0
5	1.4	2.8	3.1	0.4	3.7	0.6	2.5	-1.8	4.2
6	0.5	1.0	0.7	0.3	1.6	0.9	-1.2	0.3	1.5
7	0.6	1.1	0.5	0.5	1.6	1.0	-1.5	0.4	1.9
8	1.3	1.1	-0.4	1.6	5.3	5.7	-3.6	0.5	4.1
9	1.9	0.3	-1.2	1.4	4.3	5.4	-3.1	0.7	3.9
10	0.4	1.8	-0.3	2.1	6.1	6.4	-4.3	1.2	5.6
11	1.5	1.7	0.5	1.2	0.7	0.3	-3.1	-1.4	1.7
12	4.4	4.4	-4.8	9.2	0.3	5.2	-3.7	0.0	3.8
13	0.9	-0.8	-3.3	2.6	0.6	3.9	-0.6	0.8	1.4
14	3.5	2.9	0.8	2.1	0.8	0.0	-2.3	-2.6	0.3
15	0.3	1.0	**-1.8**	2.8	-0.6	1.2	-2.9	1.6	4.5
16	1.6	1.2	**-0.8**	2.0	-0.9	0.2	-2.6	0.6	3.3
17	0.2	0.8	**-1.1**	1.9	-0.6	0.5	-1.8	1.0	2.8
18	0.9	1.0	**-1.5**	2.5	-0.8	0.7	-2.7	0.9	3.7
19	0.2	1.7	2.0	0.3	3.7	1.7	0.5	-1.2	1.7
20	0.4	0.5	0.3	0.1	1.0	0.7	-2.7	0.7	3.4
mean	1.163678	1.615221	-0.08366	1.766839	1.975147	2.074574	-1.55676	0.234023	3.022905
sd	1.143371	1.347505	2.102968	1.981729	2.447006	2.09345	2.055391	1.488398	1.566772

CAD Amplitude

Single averages during CAD drawing, amplitude of components.

CAD Amplitude

Subj	N-400 uV	N-150 uV	P-40 uV	N-150-P-40	N+40 uV	P-40-N+40	P+120 uV	N+300 uV	P+120-N+300
1	-0.6	-2.4	-1.6	0.8	0.2	1.8	-1.2	2.0	3.2
2	1.2	-0.1	0.6	0.7	0.7	0.1	-0.7	0.3	1.0
3	-0.4	0.4	0.3	0.1	1.4	1.1	-0.9	1.5	2.3
4	0.2	-1.3	-3.5	2.2	-3.3	0.2	-4.8	2.6	7.4
5	0.3	-0.4	-1.3	0.9	1.2	2.5	-1.4	1.0	2.4
6	0.4	-0.7	-0.4	0.3	0.1	0.5	-2.8	0.8	3.6
7	-1.2	-1.4	-0.6	0.8	0.8	1.4	-2.6	2.6	5.1
8	0.1	-1.2	-0.6	0.6	1.1	1.7	-2.8	2.9	5.7
9	-1.3	0.3	-0.4	0.7	-1.4	1.0	-3.1	3.8	6.9
10	-0.3	0.6	0.2	0.4	-0.4	0.6	-2.7	1.0	3.7
11	0.2	0.2	-0.6	0.8	-0.8	0.2	-1.9	1.5	3.4
12	-0.7	-0.7	-1.8	1.0	-0.4	1.3	-2.6	0.9	3.5
13	-0.2	-1.1	-1.7	0.6	-1.6	0.1	-4.9	1.4	6.3
14	-0.1	-0.6	-0.8	0.3	0.3	1.1	-1.8	0.5	2.3
15	0.7	0.0	-0.3	0.3	-0.1	0.2	-0.4	1.2	1.6
16	0.1	-0.1	-0.3	0.2	0.0	0.3	-0.3	1.1	1.4
17	0.6	-0.6	-2.4	1.8	-2.4	0.1	-3.7	3.0	6.7
18	1.4	-1.1	-3.7	2.6	-4.1	0.4	-5.5	2.3	7.7
19	0.8	-0.1	0.8	0.8	1.1	0.3	-3.4	1.6	4.9
20	0.8	-0.1	-0.6	0.5	0.1	0.7	-2.1	-0.3	1.8
mean	0.113668	-0.51034	-0.9335	0.820797	-0.37914	0.778002	-2.47425	1.57859	4.052837
sd	0.717394	0.735568	1.213176	0.663864	1.515027	0.681448	1.489878	1.015927	2.14359

Single averages during freehand drawing, areas of components. Area above or below the zero reference line are marked with a + or – sign. Areas before or after trigger are calculated separately

DRAW	Areas			
Subj	Pre uV*ms +	Pre uV*ms -	Post uV*ms +	Post uV*ms -
1	394.7	-33.3	231.5	114.9
2	1146.4	54.4	904.5	-106.3
3	746.8	71.0	420.5	-5.5
4	196.5	0.0	58.4	-11.6
5	755.3	71.0	265.5	-380.0
6	100.8	40.6	-67.7	-5.9
7	117.8	51.7	-64.5	-56.5
8	231.1	54.0	137.3	-260.8
9	250.8	-31.2	32.9	-280.2
10	340.0	57.1	194.4	-344.6
11	614.2	71.0	-160.9	-651.1
12	1217.6	-246.2	-184.4	-968.3
13	92.5	-254.7	-35.6	137.3
14	1334.1	71.0	-174.3	-1001.2
15	99.6	-45.8	173.2	3.3
16	392.9	31.5	-93.5	-91.8
17	44.3	-16.5	25.7	58.1
18	190.5	-41.9	-117.6	-90.9
19	512.7	66.1	249.5	66.5
20	19.5	16.8	-40.3	-199.1
mean	439.9092	-0.66558	87.72997	-203.682
sd	406.289	94.85745	255.8481	328.8431

Single averages during CAD drawing. Calculated areas

Subj	Pre uV*ms +	Pre uV*ms -	Post uV*ms	Post uV*ms
1	-38.966984	-594.418954	285.069115	44.239963
2	92.723304	-90.711671	-46.419411	-93.536894
3	10.855312	-92.278677	112.942185	35.85328
4	-41.110601	-474.24352	343.130694	-722.685859
5	16.255154	-270.455197	189.469578	18.930707
6	18.834418	-46.962564	-38.669098	-259.590908
7	-46.820599	-625.243662	611.56302	-54.077702
8	-27.323901	-376.476809	460.596516	-42.817274
9	-42.880718	-955.207787	951.973558	-114.313849
10	-1.116661	-56.798012	24.379697	-137.601456
11	-26.830819	-73.917482	58.35198	-145.414803
12	-47.281777	-449.955121	-18.817936	-323.902869
13	-38.076352	-475.46009	203.616592	-785.552005
14	-45.422048	-225.725477	-37.515345	-23.38365
15	19.695258	-19.190805	-2.784983	-27.867251
16	-39.345395	-215.234622	55.288609	28.178658
17	-48.329918	-696.028306	469.665766	-470.581104
18	101.366645	-506.646902	339.95202	-793.090118
19	116.918595	21.196808	210.82391	-155.568392
20	107.047557	6.172075	-103.851305	-432.119343
mean	2.0095235	-310.879339	203.4382581	-222.745043
sd	57.75876943	277.1086776	267.3109457	276.548269

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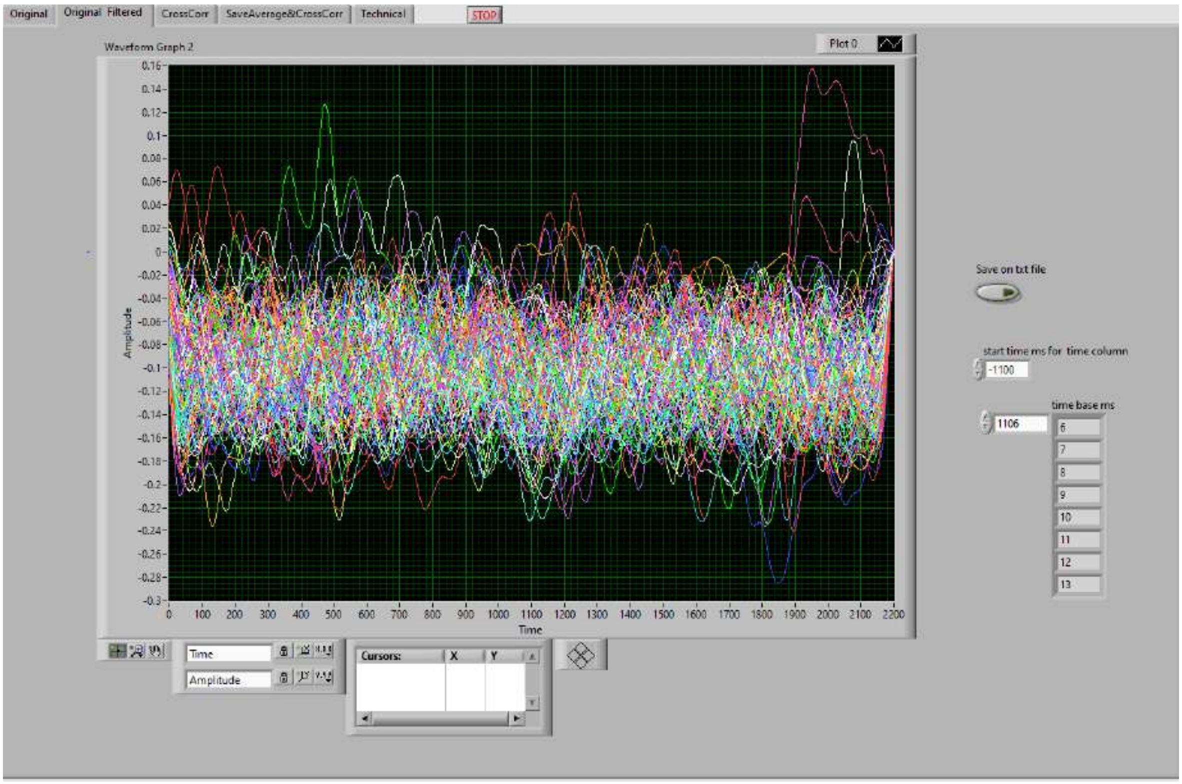
Latency, amplitude and areas calculated from the grand average traces.

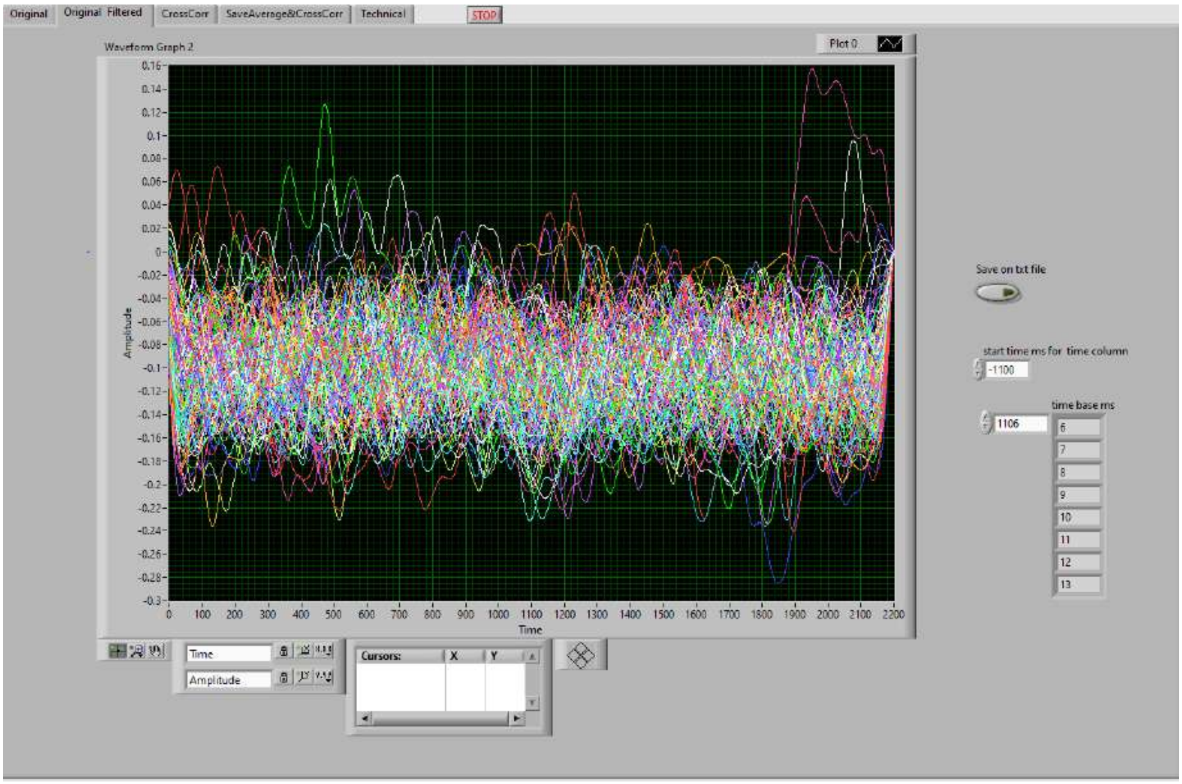
LATENCY							
DRAW	N-400 ms	N-150 ms	P-40 ms	N+40 ms	P+120 ms	N+300 ms	
GA	-415	-136	-46	30	96	283	
CAD							
GA	-591	-206	-46	19	102	307	
AMPLITUDE							
DRAW	N-400 uV	N-150 uV	P-40 uV	N-150-P-40	N+40 uV	P+120 uV	N+300 uV
GA	0.909511	1.202407	0.053622	1.1	1.784358	-0.85054	-0.08757
CAD							
GA	0.460593	-0.730145	-0.784897	0.1	-0.52263	-2.2067	0.936311
AREA	Pre uV*ms +	Pre uV*ms -	Post uV*ms+	Post uV*ms -			
DRAW							
GA	439.162133	0	87.649885	-203.601962			
CAD							
GA	1.952441	-310.95858	203.902323	-222.209108			

Experiment 3

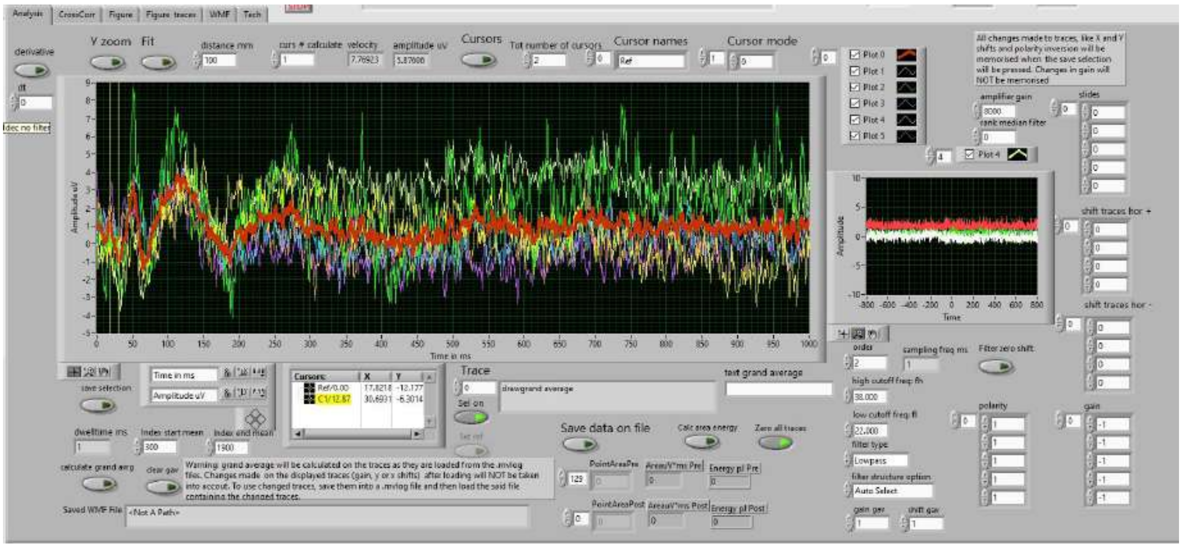
Somatosensory evoked potentials after start of movement, recording cortical activity elicited by haptic afferents from hand. Performed in 6 subjects.



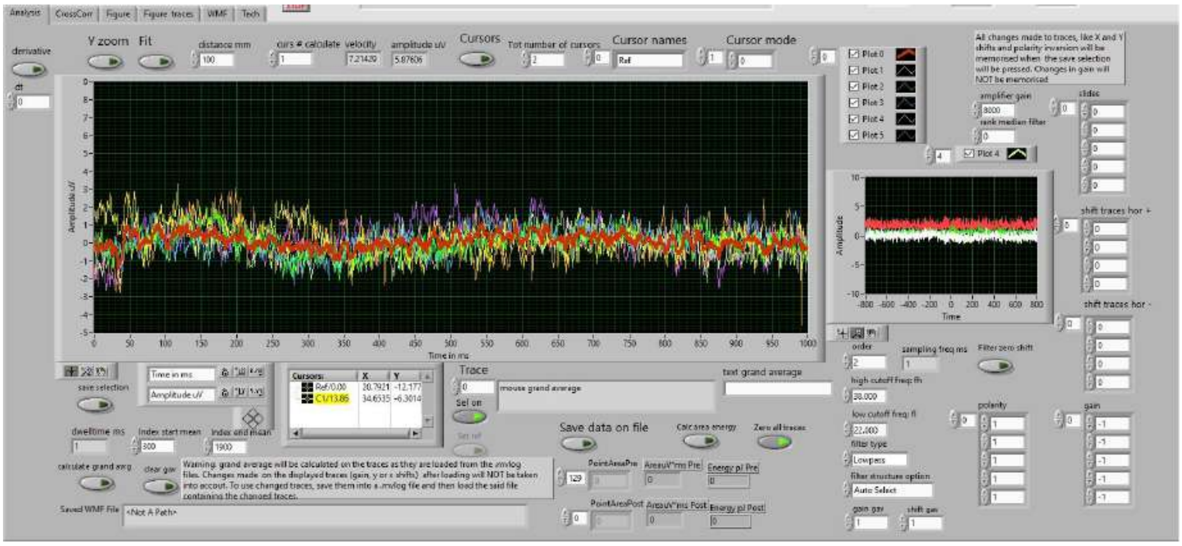
All traces from a single recording session during freehand drawing. No recognisable events are evident in these traces. Only averaging will allow their detection.



Single traces from a CAD session. No events can be recognised.



Freehand drawing with pen and tablet. Single averages of the 6 subjects, and superimposed the grand average as thick red trace. The vertical lines mark the N20 and P30 peaks



Drawing with CAD. The 6 single averages are superimposed, and on top is the red trace of grand average.

Latencies of the single averages in milliseconds

DRAW	ms						
Subj	N20	P30	N50	P70	N120	P200	N300
1	19.2	33	43	72	118	188	275
2	20.5	27	44	63	105	181	264
3	19.1	27	50	69	118	188	270
4	20.2	34	50	67	114	183	258
5	20.1	30	53	68	120	188	280
6	20.3	32	52	68	116	178	275
Mean	19.9	30.5	48.66667	67.83333	115.1667	184.3333	270.3333
	0.596657	3.016621	4.179314	2.926887	5.382069	4.320494	8.115828
CAD							
1	19.1	33	56	73	118	181	248
2	19.9	33	56	67	112	211	266
3	19.6	30	58	72	124	224	298
4	19.8	26	42	53	121	190	276
5	19.4	27	53	75	113	190	276
6	19.9	30	51	79	124	193	270
Mean	19.61667	29.83333	52.66667	69.83333	118.6667	198.1667	272.3333
	0.318852	2.926887	5.785038	9.130535	5.278889	16.04265	16.26858
T stud	0.329121	0.705779	0.199788	0.620484	0.281964	0.068706	0.793052
decrmt%	99%	98%	108%	103%	103%	108%	101%

Amplitudes of the single averages in microvolts

DRAW	uV						
Subj	N20	P30	N50	P70	N120	P200	N300
1	0.764332	-0.93723	1.339914	3.849942	4.778414	3.748984	2.320346
2	2.789606	-1.15262	8.61042	0.284856	7.899008	2.946427	6.731323
3	0.543626	-1.02936	3.645943	2.181255	4.11378	0.580772	1.303957
4	1.748643	-1.36996	3.177786	1.006853	4.911445	1.708164	5.426909
5	2.808862	-0.34547	1.80271	2.319044	3.767925	1.723832	0.656895
6	1.665986	-0.80412	3.466569	1.652209	3.522355	1.461771	1.126035
mean	1.720176	-0.93979	3.67389	1.88236	4.832155	2.028325	2.927578
sd	0.962348	0.349283	2.592604	1.226614	1.598686	1.132713	2.534623
CAD							
1	2.661281	-0.36609	1.24162	1.12157	1.431305	0.371857	0.325706
2	0.908071	-0.85175	0.601736	0.456721	0.474117	0.135365	0.394955
3	1.055071	-0.86241	1.010116	0.113624	1.123956	0.1415	0.286567
4	2.002435	-1.13979	0.998507	1.405501	0.0415	1.014569	0.940997
5	1.89809	-0.21996	1.670381	0.299292	1.055259	1.05891	0.358601
6	1.161922	-2.11107	1.243948	0.186693	1.644192	0.562033	0.758678
mean	1.614478	-0.92518	1.127718	0.597234	0.961722	0.547372	0.510917
sd	0.684616	0.674041	0.354443	0.5365	0.600984	0.411205	0.27116
	0.830888	0.963316	0.038386	0.040553	0.000244	0.01311	0.04261
decrmnt %	94%	98%	31%	32%	20%	27%	17%