Universidade do Minho
Escola de Psicologia

Alexandra Maria Marques Fernandes

Haptic working memory: Performance in interference tasks and span tasks with everyday objects

Novembro de 2011

Haptic working memory: Performance in interference tasks and span tasks with everyday objects

Alexandra Maria Marques Fernandes

UMinho|2011

Universidade do Minho
Escola de Psicologia

Alexandra Maria Marques Fernandes

Haptic working memory: Performance in interference tasks and span tasks with everyday objects

Tese de Doutoramento em Psicologia
Especialidade em Psicologia Experimental e Ciências Cognitivas

Trabalho efetuado sob a orientação do
Prof. Doutor Emanuel Pedro Viana Barbas de Albuquerque

Outubro de 2011

É AUTORIZADA A REPRODUÇÃO PARCIAL DESTA DISSERTAÇÃO APENAS PARA EFEITOS DE INVESTIGAÇÃO, MEDIANTE DECLARAÇÃO ESCRITA DO INTERESSADO, QUE A TAL SE COMPROMETE;

Universidade do Minho, ___/___/______

Assinatura: ____

Acknowledgements

Uma hipótese
A alegria é um catalisador de uma experiência científica; a tristeza, um inibidor.
A tristeza encolhe; como pode um homem triste descobrir algo?
Só quem é alegre arrisca.
A tristeza é anticientífica.

Gonçalo M. Tavares, em *Breves notas sobre ciência*

Apresento o meu agradecimento ao meu orientador, Professor Pedro B. Albuquerque. Agradeço não apenas a disponibilidade, o pragmatismo e o encorajamento ao longo dos últimos quatro anos, mas também ter-me permitido estudar memória táctil no seu grupo de trabalho.

Um agradecimento aos meus pais, Olívia e José, pelo apoio constante e incondicional desde sempre. À minha irmãzinha, Rita, obrigada pela curiosidade e pelas dúvidas sobre o meu trabalho, que por vezes me obrigaram a grandes esforços explicativos. Ao Filipe, namorado, amigo, companheiro e camarada, obrigada por todo o carinho, e por me trazer o sol e a luz, mesmo nos dias mais sombrios.

Obrigada à Helena, minha companheira de trabalho e de escrita da tese, pela visão crítica e pelos comentários pertinentes, e à Célia pelas profundas discussões teóricas. Agradeço também à Sofia e ao Paulo, à Cláudia, à Alexandra, ao Karlos e aos restantes elementos do Grupo de Investigação em Memória Humana da UMinho, pelo incentivo e desafio constantes. Quero deixar ainda um agradecimento à Joana Osório e à Joana Vieira pela companhia preciosa que foram e pela disponibilidade absoluta na participação em praticamente todos os meus estudos piloto. Não quero deixar de referir ainda o apoio empático do grupo *Doutorandos Anónimos*, em especial da Rita, da Ana Francisca e da Carla.

Ao meu grupo de amigos dos tempos do curso e agora para a vida - Leandra, Márcio, Sílvia, Pedro, Helena, Carlos, Aninha, e Andreia - um obrigada sentido pelas palavras que me disseram e escreveram ao longo deste percurso, sempre a sugestão certa no momento certo.

Expresso a minha gratidão eterna aos meus *catalisadores da alegria*: Diana, Hugo, Sofia, Luís, Carla, Filipe, Elsa, Rita e André, por estarem sempre presentes na minha vida.

Finalizando, um agradecimento direccionado a todos os alunos e ex-alunos da UMinho, a colegas, amigos e conhecidos que simpaticamente colaboraram nas imensas experiências que levei a cabo nos últimos quatro anos. Sem eles este trabalho não teria sido possível.

A final thank you note to Professor Charles Spence, from the Crossmodal Research Lab at the University of Oxford; to Professor Astrid Kappers, from the Physics of Man department at the University of Utrecht; and to Professor Rebecca Lawson, from the Visual Perception Lab at the University of Liverpool, for allowing me to visit their laboratories and to work with them, contributing to my work with their ideas, suggestions, and different approaches to research.

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

O presente trabalho foi financiado pela Fundação para a Ciência e Tecnologia através da bolsa com a referência *SFRH / BD / 35918 / 2007*.

This work was funded by Foundation for Science and Technology, with the grant SFRH / BD / 35918 / 2007.

Title

Haptic working memory: Performance in interference tasks and span tasks with everyday objects

Abstract

In this work, human haptic working memory is analysed in interference and span tasks, aiming to systematically study memory for touch in natural conditions, and to examine how haptic information is encoded and processed in human memory.

The first part of this thesis consists in a literature review of data on haptic perception and haptic memory. Our approach to this review implied a systematisation of the main variables manipulated in tactile and haptic studies, followed by a critical review of studies on memory for touch.

The first group of experiments, evaluating the impact of interference tasks in haptic recognition is described in Part II. Participants were required to sequentially touch lists of 50 common (e.g., *comb*) or uncommon (e.g., *plastic onion*) everyday objects, either in single task or interference task conditions, and then were asked to perform an immediate incidental haptic recognition memory task, by touching a new list of 50 objects (25 presented and 25 non-presented objects) and to indicate if each object had been touched before. The interference tasks were always performed at encoding and could be haptic (evaluating paper samples), motor (performing a concurrent movement), verbal (evaluating pseudo-word pairs), or visuospatial (evaluating three-dimensional stimuli images). Results showed that participants were able to perform these tasks with a high accuracy rate, either for common or uncommon objects. For common objects, only haptic interference impaired haptic recognition. For uncommon objects, haptic recognition was affected by haptic, verbal and visual interference tasks, but not by motor interference. A final analysis, considering direct comparisons between object types for each interference condition revealed that common objects systematically present higher recognition rates, and are less affected by interference than uncommon objects. Overall, these studies suggest a haptic specificity in working memory, and an object familiarity mediation of the participant's performance.

The third part of this thesis reports a group of exploratory studies on haptic span, recurring to immediate serial recall and reconstruction of order tasks. Considering the relevance of verbal representations for everyday objects, the participant's performance was studied in single task and articulatory suppression conditions. In immediate serial recall tasks participants were asked to touch lists of common objects (e.g., *ball*), starting with a list extension of two objects, and going up to ten objects, according to the participant's performance. Results revealed an haptic span of approximately five items in single task and of four items in articulatory suppression conditions. In reconstruction of order tasks, after the list presentation, all touched objects were available again, and the participants had to order them according to the initial presentation. This task, not implying item identification (naming), allowed a comparison between common and uncommon object's span. Results showed that similar spans exist for both conditions, with about six items being recalled in single task, and about five items in the articulatory suppression conditions.

The present work is a contribute to the field of haptic cognition, specifically haptic memory, by presenting a first attempt to systematically study working memory for touch by adapting classical paradigms in the study of human memory to the haptic sensory modality. Throughout this work, empirical and theoretical topics regarding touch experiments are discussed and future research paths in this field are suggested.

Título

Memória de trabalho háptica: Desempenho em tarefas de interferência e tarefas de capacidade com objectos quotidianos

Resumo

Neste trabalho analisa-se a memória de trabalho háptica em humanos, procurando estudá-la de forma sistemática e em condições naturais, explorando a forma como a informação háptica é codificada e processada na memória humana.

A primeira parte desta tese consiste numa revisão da literatura existente nas áreas de percepção e memória táctil e háptica. A abordagem à revisão teórica passou pela sistematização das variáveis centrais nos estudos sobre tacto, seguida de uma revisão crítica do estudo da memória táctil.

O primeiro grupo de experiências avalia o impacto de tarefas de interferência no reconhecimento háptico e é descrito na Parte II. Os participantes tocaram sequencialmente uma lista de 50 objectos quotidianos comuns (e.g., *pente*) ou incomuns (e.g., *cebola de plástico*), em condições de tarefa simples ou em condições de interferência. De seguida foi-lhes solicitada a realização de uma tarefa de reconhecimento háptico imediata e incidental, tocando uma nova lista de 50 objectos (25 apresentados previamente e 25 não apresentados) e indicando para cada objecto se este havia sido tocado anteriormente. A tarefa de interferência foi realizada durante a fase de codificação dos objectos e poderia ser de natureza háptica (avaliação de amostras de papel), motora (realizar um movimento específico), verbal (avaliação de pseudo-palavras), ou visuo-espacial (avaliação de imagens de estímulos tridimensionais). Os resultados demonstram que os participantes foram capazes de realizar a tarefa de reconhecimento háptico com elevadas taxas de acerto, quer para objectos comuns, quer para objectos incomuns. Para os objectos comuns, apenas a interferência háptica prejudicou o reconhecimento háptico. Para os objectos incomuns, o reconhecimento háptico foi prejudicado pela interferência háptica, verbal e visuo-espacial, mas não pela interferência motora. Uma última análise, comparando directamente o desempenho para objectos comuns e incomuns para cada tipo de interferência, revelou que os objectos comuns produzem sistematicamente melhores taxas de reconhecimento e são menos prejudicados pela interferência do que os objectos incomuns. De uma forma geral, os estudos apresentados na segunda parte deste trabalho sugerem a existência de especificidade háptica na memória de trabalho, assim como um efeito mediador da familiaridade dos estímulos no desempenho dos participantes.

A terceira parte desta tese descreve um conjunto de estudos exploratórios sobre tarefas de capacidade de memória háptica, recorrendo a tarefas de evocação serial imediata e a tarefas de ordenação. Considerando a relevância das representações verbais para os objectos quotidianos, os participantes nestes estudos realizaram as tarefas de capacidade em condições de tarefa simples e com supressão articulatória.

Nas tarefas de evocação serial imediata, os participantes tocaram listas de objectos comuns (e.g., bola), começando a tarefa com listas com a extensão de dois objectos, que podiam ser aumentadas até um máximo de 10 objectos, dependendo do desempenho individual. Os resultados demonstram que a capacidade háptica é de aproximadamente cinco itens em condições de tarefa simples, e de quatro itens em condições de supressão articulatória. Nas tarefas de ordenação, após a apresentação das listas, todos os objectos tocados estão disponíveis para o participante, que deverá ordená-los de acordo com a apresentação inicial. Nesta tarefa, uma vez que não é necessária a identificação dos itens, foi possível comparar o desempenho com objectos comuns e incomuns. Os resultados mostram que o número de itens correctamente ordenados é idêntico para objectos comuns e incomuns e corresponde a aproximadamente seis itens em condições de tarefa simples e a cinco itens em condições de supressão articulatória.

Este trabalho apresenta-se como um contributo para o campo da cognição háptica, especificamente da memória háptica, apresentando uma primeira tentativa de estudar sistematicamente a memória para o tacto, adaptando paradigmas clássicos no estudo da memória humana à modalidade sensorial háptica. Ao longo deste trabalho, tópicos empíricos e teóricos acerca das experiências com tacto serão discutidos e serão sugeridos caminhos de investigação futura nesta área.

Contents

Part I

Part II

Part III

Part IV

Part V

List of Figures

List of Tables

O centro do olho e o canto do olho

(...)
Na Ciência, como no mundo das invenções, observar pelo canto do olho é ver o pormenor diferente, aquele que é o começo de qualquer coisa de significativo.
(...)

Gonçalo M. Tavares, em *Breves notas sobre ciência*

PART I

INTRODUCTION

Through history, touch has been considered a basic and lower form of perception (Paterson, 2007). In Aristotle's *De Anima* in 350 BC (Aristotle, 1907), the hierarchy of the five senses presents touch in the lowest level. At the same time, Aristotle notes that touch in humans is twofold, separating pure tactile sensation from carnal appetites, and considering this complexity of touch, only observed in humans, as a proof of superior intelligence. Others presented touch as the first sense, from which the others would develop (e.g., Aquinas). It was considered a primal sense, and a first mode of interaction with the world for newborns. It has also been regarded as a communication sense since the early Greek philosophers and the connection between touch, aesthetic pleasures and the flesh was address by Aristotle's in *De Sensus* (Paterson, 2007). The association between touch and pleasure throughout medieval times resulted in a link of touch and shame and led up to a great loss of knowledge about tactile senses, as monks were forbidden to transcribe any texts that mentioned the skin senses (Jütte, 2008; Krueger, 1982).

In the 18th century, a new scientific interest on touch appeared and Ernst Weber was the first physiologist to entail studies on touch. Perception through touch was considered as a whole, with no differentiation between the sense of pain, pressure, temperature and tactile properties (Jütte, 2008). Weber presented the concept of just noticeable differences (JND) after a series of studies on the sense of pressure. The JND corresponds to the minimum difference between two physical stimuli that can be perceived by a participant. Weber states that the JND between two stimuli is proportional to the magnitude of the stimuli, implying that subjects can easily discriminate small differences in small or less intense stimuli, but need larger physical differences to be able to perceive changes in larger or more intense stimuli (Weber, 1834/1996; 1905/1996). This postulate has been known has the just noticeable difference law or Weber's Law. The pioneer work of Weber resulted in a boost of physiological research on touch and other senses.

In 1892, Max Dessoir presents, for the first time, the term "haptic", considering a similarity with the terms "optic" and "acoustic" (Jütte, 2008). Dessoir describes the need to have a term that defines all subsenses of touch - muscle sense, temperature sense, pain sense - and presents "haptic" as a concept to define the science of human touch (Jütte, 2008). Today, the concept of haptics is more intrinsically associated with the notion of active touch and active perception of stimuli, recurring to tactile, proprioceptive and kinaesthetic cues.

The first systematic psychological studies on touch are attributed to David Katz in 1925, in his monograph *Der Aufbau der Tastwelt*, translated by Krueger with the title *The world of touch* (Katz, 1989/1925). With this work, Katz intended to show that the separation of senses with vision and audition being rated as "upper level" and the other senses as "lower level", was not correct, and that touch was a complex system, able to perform many different tasks. Katz presents a large number of experiments, comparing vision and touch, separating tactile qualities from identifying characteristics in touch, mentioning the importance of movement in tactile perception, and analysing the perception of temperature and vibration. Katz's work was similar to Gibson’s (1966) attending to the relevance of higher-order aspects in perception and emphasising the role of movement in touch.

The initial interest in touch, as well as other senses, was centred in physiological and later psychophysical aspects of perception. One of the first studies on memory for touch was presented by Bliss, Crane and Mansfield (1966). Following the works of Sperling (1960) on visual immediate memory, that demonstrated that participants could retain more information than that they could report about a briefly presented stimuli array, Bliss et al. (1966) intended to analyse if the same type of pattern existed for brief tactile multiple presentations. This study showed that there was a brief sensory register for touch, similar to iconic memory in vision, but it seemed that the tactile storage had lower capacity (Bliss et al., 1966).

One of the central difficulties in research with haptics has been experimental control. Researchers chose to use passive touch, to restrain movements, and to present abstract or simplified versions of objects as stimuli to gain more control over the experiments. These manipulations contributed to an understanding of touch as a weak form of perception that required a long exploration time. In the 80’s and 90’s, the works of Lederman and Klatzky, brought a new approach to psychological research on touch. In a series of very interesting and leading works in the field of haptics (e.g., Lederman & Klatzky, 1987; Klatzky, Lederman, & Metzger, 1985) these authors revealed that touch is a very effective modality, allowing quick and correct identification and recognition of everyday objects.

The history of touch research has been marked by an initial period of intense progress in physiology and psychophysics (e.g., the works of Weber, von Frey and Gesheider), and an interest in blind individuals tactile abilities and their connection to education (e.g., the works of Braille). Only recently, research on touch has been centred in more complex cognitive processes associated with perception, like identification, categorisation and memory.

In the last two decades, experiments on touch have been more frequent and the number of researchers working in this area has grown significantly (Heller & Ballesteros, 2006). The advances in areas as robotics, human-machine interactions, and virtual environments, brought a great number of new techniques and procedures that allow researchers to further explore the sense of touch and to increase the knowledge about how we perceive and process the stimuli we access through touch alone.

The first part of this thesis comprises a literature revision on touch and memory, analysing results regarding the main variables that have been studied in touch. As such, we will examine the differences and similarities in haptic processing according to the selected participants, exploring studies with children and adults, female and male participants and between blind and sighted individuals. Another relevant variable in touch is the type of stimuli we evaluate, and here we will consider studies with abstract and concrete stimuli, with two-dimensional and three-dimensional objects, and with familiar and unfamiliar stimuli. The restrictions on haptic exploration are another interesting variable, and we will consider the differences between free exploration, restricted exploration, and conditions of passive touch (with no voluntary movement from the participants). We will look upon sensory immediate memory for touch and analyse some classical studies and more recent developments. Finally, we will concentrate the literature revision on memory for touch, reviewing the published studies on this topic and comparing results on immediate sensory memory, short-term memory, working memory and long term memory experiments.

REFERENCES

Aristotle. (1907). *De Anima*. (R. Hicks, Trans.). London: Cambridge University Press.

Bliss, J., Crane, H., & Mansfield, P. (1966). Information available in brief tactile presentations. *Perception & Psychophysics, 1,* 273-283.

Gibson, J. (1966). The senses considered as perceptual systems. Boston: Houghton Mifflin Company.

Heller, M., & Ballesteros, S. (2006). Preface. In M. Heller & S. Ballesteros (Eds.), *Touch and blindness: psychology and neuroscience*. New Jersey: Lawrence Erlbaum Associates.

Jütte, R. (2008). Haptic perception: an historical approach. In M. Grünwald, (Ed.). *Human Haptic Perception: Basics and Applications*. (pp. 3–13). Basel: Birkhäuser.

Katz, D. (1989). *The world of touch* (L. Krueger, Trans.). Hillsdale: Lawrence Erlbaum. (original work published 1925)

Klatzky, R.L., Lederman, S.J., & Metzger, V. (1985). Identifying Objects by Touch - an Expert System. *Perception & Psychophysics*, *37*(4), 299–302.

Krueger, L. (1982). Tactual perception in historical perspective: David Katz's world of touch. In W. Schiff & E. Foulke (Eds.), *Tactual perception: a sourcebook* (pp. 1–54). New York: Cambridge University Press

Lederman, S.J, & Klatzky, R.L. (1987). Hand movements: a window into haptic object recognition *Cognitive Psychology*, *19*(3), 342–368.

Paterson, M. (2007). *The senses of touch: haptics, affects and technologies*. haptics, affects and technologies. New York: Berg Publishers.

Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs: General and Applied*, *74* (11), pp. 1-29.

Weber, E. (1996). *E. H. Weber on the Tactile Senses*. (H. Ross & D. Murray, Ed & trans.). Erlbaum (UK) Taylor & Francis. (original works published in 1834 and 1905)

PART I

LITERATURE REVISION

Tactual perception:

A review of experimental variables and procedures[1]

ABSTRACT

This paper reviews literature on tactual perception. Throughout this review we will highlight some of the most relevant variables in touch literature: interaction between touch and other senses; type of stimuli (abstract stimuli as vibrations, two and three dimensional stimuli, and concrete stimuli such as the relation between familiar and unfamiliar stimuli and the haptic perception of faces); type of participants (studies with blind participants; studies with children and adults, and possible gender effects); and type of tactile exploration (conditions of active and passive touch, the relevance of movement in touch and the relation between exploration and time). This review intends to present an organised overview on the main variables in touch experiments, to guide the design of future works on tactual perception and memory, attending to the main findings described in literature.

When we think about touch we have to apprehend it as a complex system with more than one sense: touch involves pain perception, temperature perception, proprioception, kinaesthetic perception and, finally, tactile perception. Other relevant conceptual definitions must be established regarding touch. The concepts *tactile*, *haptic*, and *tactual* are frequent in touch related literature and are often presented as synonymous. During the present work, we will use them as distinct concepts. Tactile perception refers to the extraction of material properties from the stimuli, such as texture (as opposed to geometrical properties such as shape). Tactile perception results from cutaneous variations only (Loomis & Lederman, 1986) and is associated with situations of passive touch, in which the participants cannot explore the objects, keeping their hands or fingers still while the stimuli are pressed against their skin. However, most stimuli properties are extracted through a combination of cutaneous and movement cues, this combination results in more than just a sum of kinaesthetic and tactile inputs, in the sense that only a complex integration of these cues allows the perception of objects in space and in relation to each other (Kaas, Stoeckel, & Goebel, 2008). To this type of perception through touch we call haptic perception (Loomis & Lederman, 1986). Haptic perception is the most natural form of perception through touch and is more related with free exploration procedures. The term tactual perception is a more generic concept, and refers to all types of perception derived from cutaneous (tactile) and kinaesthetic (movement) cues, and is used to describe overall perception by touch.

Touch has been an unattended sensory modality in cognitive research. Most of touch literature comes from perception areas, attempting to compare touch with other sensory modalities, although the particularities of touch have also been explored. Touch is relevant in everyday tasks, and haptic memory allows us to remember the feeling of objects and the touch of other people and is crucial in our everyday life. From picking

---

[1] Paper submitted to *Psicothema*

a coin in our wallet to evaluating the force we need to apply to open a door, we rely on touch in various everyday tasks. A quick search in the Web of Knowledge database (September 2011) provides a clear overview of the scarcity of papers on this topic: a general search for the topics *tactile memory, haptic memory, touch memory*, or *tactual memory* results in 933 documents, of which only 136 are published articles. Through the four years in which the present work was developed (from 2008 to 2011), only 28 articles on memory for touch appear in this database.

Memory models and theories ideally present a scheme of how all types of information are processed and retained for short and long periods of time. Traditionally, research on human memory has been conducted mainly with verbal and visual stimuli. Theoretical hypothesis and implications have been drawn from empirical data with these stimuli, and its conclusions have been generalised to all types of sensory perception. In this context, experiments targeting other sensory modalities besides vision and audition might imply a challenge to the pre-existing memory models and as such enhance them, contributing to a better knowledge of human memory in general.

This literature revision aims to contribute to the systematisation of information regarding memory for touch, first by analysing the main variables manipulated within perceptual paradigms (namely the interactions of touch with other senses, the type of stimuli, the type of participants, and the tactile exploratory conditions), and their implications for memory studies.

1. TOUCH AND THE OTHER SENSES

Our everyday interaction with objects is mainly multisensory. We are able to simultaneously perceive the colour of a fruit, it’s fragrance, it’s softness, the sound of the bite, and it’s sweetness, and all of these different perceptions seem to be deeply integrated to the point that we are able to recall an apple’s taste and smell just by seeing it’s picture.

The interactions between the senses are crucial to our knowledge of cognitive processes such as perception and memory. The ability to share stimuli properties between senses, and at the same time the specificity that each sensory modality brings to our everyday experience are relevant topics in human cognition. Possibly due to the complex relations, interactions, and distinctive features among sensory modalities, the topic of multisensory and crossmodal perception is not yet very developed in higher order processes as memory.

The combination of information from different sensory modalities is useful and allows the correction of biases generated in a particular modality. Having a variety of sources to perceive the same object or event allows us to reduce perceptual ambiguity (Helbig & Ernst, 2008), and produce more efficient responses. Through this section we will analyse research that connects touch to vision, audition, taste, and smell.

1.1. Touch and Vision

Haptic research has been mostly conducted under multimodal visuo-tactile paradigms, either comparing performance on touch and vision (James & Blake, 2004; Kappers & Schakel, 2011; Tiest & Kappers, 2007), or exploring shared representations between the two modalities (Easton, Srinivas, & Greene 1997; Lacey, Campbell, & Sathian, 2007; Whitaker, Simões-Franklin, & Newell, 2008).

Lacey et al. (2007) conducted a review on vision and touch interactions. The authors conclude that both modalities share cognitive resources and processes, based in spatial representations, and that these representations are dynamic and affected by topdown and bottom-up processes. However, the authors highlight the relevance of research that has reported differences between the two modalities and has pointed to the existence of unimodal coding and retrieval processes, referring that further research is needed to clarify these modality-specific processes (Lacey et al., 2007).

A central aspect of the connection between vision and touch is the shared spatial component, present in both modalities, but mostly explored in vision. There seems to be an equivalence between touch and vision for spatial processing and many researchers have explored this topic. Easton et al. (1997) in a study consisting in the presentation of words either visually or haptically, reported no differences between modalities and argued in favour of shared representations in vision and touch. In a second study (Easton, Greene, & Srinivas, 1997), aware of the relevance of verbal processing in the presentation of words, the authors explore visual and haptic representations testing participants with two-dimensional patterns and three-dimensional objects. Results showed that for two-dimensional patterns cross-modality priming was strong, but in three-dimensional objects modality-specificity was observed, indicating that both shared and unique processes determine crossmodal integration. Giudice, Betty and Lommis (2011) in a study with blind and sighted participants revealed that spatial images are shared between vision and touch and, attending to the data from the blind participants group, this equivalence was not a consequence of visual recoding of haptic information, since the pattern was equivalent for both participants' groups. Likewise, Cattaneo and Vecchi (2008), asked participants to memorise a number of locations in a 5x5 matrix either visually or haptically and to report them in an empty matrix. Results showed that visual performance was overall better than haptic performance, that representations were modality-dependent and that some information was shared between modalities, indicating that both supra-modal and modality-specificity processes were present.

Besides spatial equivalence, other similarities have been reported for visual and haptic processing. For instance, in texture perception, Picard (2006) reported partial equivalence between vision and touch in a crossmodal matching task, in which participants had to match stimuli that were previously rated as presenting a high or low crossmodal dissimilarity. This study broadened the findings of Garbin (1988) on visuo-haptic equivalence for shape perception. A review on texture perception by vision and touch (Whitaker et al., 2008) concludes that, unlike shape perception, texture perception by vision and touch is not equivalent, but complementary. The authors point to research providing no evidence for visuo-haptic integration in behavioural tasks with familiar objects (e.g., Tiest & Kappers, 2007) and suggest that this lack of crossmodal correspondence might be due to more elaborate cognitive processes than basic perception. In a different topic, Luo and Imamiya (2003; 2004) also report that colours affect perceived haptic roughness in surfaces.

Crossmodal illusory conjunctions (considering that an item presented in one modality was actually presented in another) were also observed within touch and vision (Cinel, Humphreys, & Poli, 2002). Participants saw visual stimuli while touching tactile stimuli and after a mask had to report the shape and texture of the seen object or the orientation of the touched stimuli. Results showed that participants reported felt textures as seen and vice-versa, and these misguided reports were more frequent when visual and haptic stimuli were presented in the same hemispace. Auvray, Gallace, Tan, and Spence (2007) also describe equivalence between touch and vision in a crossmodal change blindness paradigm. Change blindness is a phenomenon characterised by the inability to detect differences in two consecutive stimuli, due to the presentation of a mask between them. This phenomenon has been studied in vision, audition and touch (Auvray et al., 2007). In this study, change blindness was reported even when stimuli were presented in different modalities (haptic and visual), and regardless of the mask presentation modality, although the phenomenon was stronger in within modality presentations. These results were interpreted as an indication that multisensory processes are in the base of change blindness.

Craddock and Lawson (2009a) argued that size perception was shared between vision and haptics after a crossmodal study in which participants were asked to recognise three-dimensional objects based on shape alone, ignoring size changes. Results revealed that size variation impaired crossmodal recognition, suggesting shared representations of size between modalities. However, the authors hypothesised that these shared representations might be either perceptual (low-level) or mediated by high-level processes.

Another group of studies has focused on the differences between touch and vision in perception and recognition tasks. Lawson (2009) evaluated depth rotation in visual and haptic conditions with morphs of everyday objects and found that for unimodal and visuo-haptic trials object discriminability and orientation changes impaired recognition, while in haptic-visual trials orientation changes had no effect. This result suggests that different processes underly haptic and visual orientation processing. In a study analysing the perception of shape and size by vision and touch (Van Doorn, Richardson, Wuillemin, & Symmons, 2010), participants were asked to evaluate the size of touched shapes selecting the touched shape from a haptic or visual set. Haptic exploration was either active or passive, and could present cutaneous information along with kinaesthetic. Performance in the visual task was better than in the haptic task when participants were allowed to passively explore the objects, but when cutaneous information was allowed in active exploration, haptic performance was better than visual.

In other study, examining visual and haptic perception of shape for three-dimensional objects resulted in a partial functional equivalence between modalities, marked by unimodal representations (Norman, Norman, Clayton, Lianekhammy, & Zielke, 2004). In this experiment participants were able to recognise objects in crossmodal conditions with high levels of accuracy, nonetheless unimodal conditions presented higher performance. Stadtlander, Murdoch, and Heiser (1998) explored visual and haptic recognition in function of age and concluded that regardless of sensory modality, young adults (20 - 35 years-old) were better than older adults (60 - 75 years-old) in object recognition. Moreover, haptic recognition presented the higher recall in both groups (younger and older participants).

Ernst and Banks (2002) developed a multisensory integration mathematical model applicable to vision and touch interactions, as well as other multimodal associations (e.g., Bresciani & Ernst, 2007). This model is based on bayesian statistics and uses the maximum likelihood estimation, arguing that visual and tactile inputs are integrated in a statistical optimal fashion (Ernst & Banks, 2002). According to this model, when two perceptual modalities are capable of processing the same stimuli, the most influent modality will be the one that present the lesser variance in perceptual estimation. This model allows a better understanding of apparently contradictory experimental findings in which vision dominates for some tasks and haptics for others. According to the maximum likelihood model, the dominant modality will be the one with more reliable information for each particular task.

Previous studies focused on the analysis of visuo-haptic interactions for stimuli features that can be encoded by both modalities: location, patterns, texture, shape, size, and orientation. For these common features, partially shared processing is described in literature, with many features presenting equivalent manipulation and representation in both modalities (e.g., location), but others maintaing modality specificity (e.g., texture).

1.2. Touch and Audition

Audiotactile interactions have been reported in two central domains: temporal and spatial. The temporal domain is related to a large group of research evaluating the perception of temporal order in tactile and auditory stimuli when presented with different time intervals (e.g., Occelli, Spence, & Zampini, 2008). The spatial domain focuses on the perceived simultaneity of tactile and auditory stimuli presented at a same location in space, and concentrate in the apparent automatic integration of this type of information (e.g., Zampini et al., 2005).

It has been shown that sound beeps can modulate the counting of tactile taps (Bresciani et al., 2005). Participants were asked to concentrate in the number of taps, and to ignore the beeps, however numerosity judgements were biased by simultaneous beep counting. As the interval between tap and beep was increased the modulation effect decreased, suggesting that simultaneously presented audiotactile information tends to be integrated (Bresciani et al., 2005). In a later study (Bresciani & Ernst, 2007) with similar procedure, the authors concluded that not only auditory signal affected tactile processing, but also tactile taps affected auditory counting, and reported that diminishing the intensity of sounds generated less interference on tactile counting, as well as affected the impact of touch on the auditory task (Bresciani & Ernst, 2007). As such, not only audiotactile integration was shown to be automatic, as it was revealed to be signal reliability dependent.

Gillmaister and Eimer (2007) reported tactile enhancement of auditory perception with two experiments analysing detectability and intensity of auditory stimuli. In the first experiment, participants had to signal if an auditory stimuli was presented in one of two time intervals. Results showed that tactile stimuli facilitated the detection of sound, and that this effect was larger on simultaneous trials (in which the tactile and the auditory stimuli were presented at the same time) than on asynchronous trials. The stimuli intensity task consisted in the evaluation, in a nine point scale, of tactile and auditory stimuli. Tactile stimulation led to higher intensity judgements of the auditory signal. Again, simultaneous presentation resulted in more modality integration, revealing that temporal synchrony is an essential condition for audiotactile integration.

Interactions between audition and touch were found to be dependent of hand position in a study presented by Sanabria, Soto-Faraco, and Spence (2005a). Participants were asked to place their hands either crossed or over the midline and had to discriminate the direction of an auditory array (sequence of sounds presented in different spatial locations), while receiving spatiotemporal congruent or incongruent tactile stimulation in the hands. Impaired performance was reported for incongruent tactile stimulation, but only in participants who did not have crossed hands. In a second experiment, the authors use the same procedure but asked participants to focus on the tactile stream, and not the auditory ones, and found that interaction effect were stronger in the crossed hands condition. The authors conclude that body posture can affect crossmodal interaction and audiotactile influences seem to be reciprocal (Sanabria et al., 2005a).

In an exploration of audiotactile integration in blind and sighted participants, Hötting and Röder (2004) asked participants to estimate the number of rapidly presented tactile stimuli, while ignoring non-relevant sound during the task. When a tactile stimuli was presented in conjunction with more than one sound, participants reported feeling more than one touch, and this effect was stronger for sighted than blind participants.

Crossmodal perception between touch and audition has also been tested with other paradigms like the saltation illusion, when one target stimulus is systematically displaced in the direction of another stimulus that is presented either at a near position or at the same time (e.g., Trojan, Getzmann, Möller, Kleinböhl, & Hölzl, 2009), the ventriloquist effect, when stimuli from two sensory modalities, presented from a same spatial location are attributed to the same source (e.g., Bruns & Röder, 2010), and apparent motion phenomenons when a sequence of presented stimuli is perceived as one stimulus in motion (e.g., Sanabria, Soto-Faraco, & Spence, 2005b). In all these paradigms, the existence of an automatic integration of auditory and tactile stimuli is reported, and the effect seems to be stronger when both stimuli are presented simultaneously, and specially when the stimuli are presented in the same spatial location, indicating a natural form of integrated perception between modalities.

1.3. Touch, smell, and taste

Olfaction and taste have been a topic of research specially in the food industry, and within this context, the study of touch has been essentially restricted to the relevance of perceived textures and temperature in the tongue while tasting food.

However, the connections between touch, smell and taste were already mentioned in literature many years ago. Gibson (1966) suggested the definition of *flavour* as a specific sense that involved inputs from taste, smell and touch. Tichener (1909) also mentioned the relevance of a combined perception of temperature, touch, taste and smell in the ingestion of coffee or fruit.

A review on the multisensory perception of flavour (Delwiche, 2004) enhances the role of touch influencing perceived flavour through temperature and texture perception. The interaction between touch and taste is obvious in a study that revealed a tactile-taste illusion. In this illusion, after putting an ice cube on the side of the tongue, a salty taste is perceived, originating a taste perception after a temperature stimulation. Besides the stronger salty sensation, the authors were able to induce perception of sweet, sour and bitter (Cruz & Green, 2000). Another reported interaction between touch and taste is that the perceived viscosity of a liquid can alter the intensity of its flavour to the taster (Bult, de Wijk, & Hummel, 2007). In a more recent review on this topic, (Auvray & Spence, 2008) also argue in favour of a multisensory perception of flavour, derived from taste, smell and tactile cues, which continuously affect each other when we are eating.

The connections between touch and smell are also explored in literature. Laird (1932) presents results of a study in which women judged the quality of silk stockings. Without the knowledge of the participants, the stockings were impregnated with soft fragrances, and women consistently evaluated identical stockings as being better when they presented a narcissus fragrance, and justified their evaluations with properties as durability or sheen, and never attending to olfactory characteristics. The evaluation of fabric softness is also affected by odours, as was shown in a study in which fabrics associated with lemon odours were evaluated as softer than fabrics associated with animal odours (Demattè, Sanabria, Sugarman, & Spence, 2006).

The understanding of the apparently automatic processes that allow interchange of information between sensory modalities, enabling reciprocal modulation in ongoing tasks, is crucial in cognitive sciences. The need to control for any multisensory interactions when trying to access processes in a specific sensory modality, as well as the exploration of these natural connections between the senses in memory processes, are obvious. The nature of sensory representations, either in their suggested amodal or higher order processing, or concerning intramodal particularities needs to be acknowledged in order to strengthen experimental designs and procedures.

2. TYPE OF STIMULI: Abstract Stimuli

2.1. Vibrations

The use of vibrating stimuli in tactile research has been mainly present in the definition of tactile thresholds (e.g., Hagander, Midani, Kuskowski, & Parry, 2000), tactile masking paradigms (e.g., Craig & Evans, 1987) or tactile pattern perception (e.g., Cholewiak, Collins, & Brill, 2001). However, vibrations have also been studied under more applied areas, for instance the use of vibration as warning signals in driving (e.g., Spence & Ho, 2008; Ho, Tan, & Spence, 2006). Also, the perception of vibration has allowed the development of communication systems for sensory deprived subjects, such as the Tadoma system, a system by which deaf-blind subjects are able to perceive speech by placing their hands on the speakers face and feeling the vibrations (e.g., Sherrick, 1975).

Vibration is useful in the perception of roughness and Katz (1925/1989) mentioned the involvement of the sense of vibration in tactile perception. Lederman, Loomis, and Williams (1982) confirmed the relevance of vibration in roughness perception, and argued that vibration allowed continuous activation of the mechanoreceptors of the skin, facilitating texture perception.

Vibrotactile stimulation has also been used within working memory paradigms. For instance Bancroft and Servos (2011), using a matching to sample paradigm, explored interference effects in working memory. Participants had to determine if two separate vibrotactile stimuli had the same frequency or not. Between the two stimuli, an interference distractor was introduced. Results show that the frequency of the distractor affected performance, with trials in which the distractor was more similar to the probe having more errors than trials in which the distractor was more similar to the target. The authors assume that the distractor is overwriting the probe stimuli, and argue in favour of an overwriting system to explain interference effects in working memory.

The use of vibrotactile stimuli, although more common with physiological (e.g., Verrillo, 1968) or psychophysical (e.g., Verrillo & Gescheider, 1975) procedures, is also reported in perception and memory research, allowing the study of touch within controlled exposition conditions.

2.2. Two-dimensional and three-dimensional stimuli

Aiming to evaluate haptic perception and cognition by itself, many researchers have chosen to collect data using artificial stimuli, created in the laboratory. These stimuli, either two- or three-dimensional, allow absolute control of stimuli properties and are very useful to understand how people discriminate single features of the objects, or how different properties are weighted and integrated.

Regarding two dimensional stimuli, two main types of stimuli can be found: raised line drawings or haptic pictures, that consist in the presentation of the contours of a drawing in a higher level to the background, allowing tactile perception; and tactile scenes, presentation of matrices or other complex stimuli that can only be explored in two dimensions.

Plaisier, Tiest and Kappers (2008) have explored the pop-out effect on haptics. The pop-out effect has been studied in vision and refers to the easier detection of a stimuli among others in a visual search: for instance, detecting a red stimuli among green ones. In this first study on haptic pop-out (Plaisier et al., 2008) it was shown that a rough item among fine items in a matrix was detected faster than the inverse, demonstrating the existence of a pop-out effect in haptics. Analysing bilateral symmetry, Ballesteros, Manga and Reales (1997) reported that for raised line shapes, perception of asymmetry was better than perception of symmetry when participants could explore the item with only one finger, and that bimanual exploration facilitated symmetry judgments, but not asymmetry ones. For unfamiliar three-dimensional stimuli, unimanual and bimanual explorations did not differ, and symmetry judgments were very accurate.

The variability of three-dimensional abstract stimuli is higher than in two-dimensional stimuli and these type of stimuli can be geometrical or abstract forms built in various materials (e.g., plastic, wood, metal) or stimuli created from the combination of toy construction blocks.

Kiphart, Auday and Cross (1988) reported a hit rate of 93% in the recognition of haptically presented three-dimensional objects, with false alarms being virtually inexistent even for delays as large as 40 seconds between item presentation and recognition for a total of 30 objects. In a later study (Kiphart, Hughes, Simmons, & Cross, 1992) the authors reported high discriminability measures, even when the stimuli are attached to a base, and the participants only had three seconds to explore them.

Regarding the discrimination of Gaussian-like shapes, attending to amplitude and width parameters, Louw, Kappers, and Koenderinck (2002) show that participants are able to haptically discriminate up to 300 shapes, being better at discriminating sharp from smooth Gaussian curves than at discriminating between small and large ones. The authors conclude that the estimation of width is central for the discrimination of shape.

Using three dimensional objects van der Horst and Kappers (2008) explored the effect of curvature in haptic perception. The participants were asked to differentiate cylinders with a circular versus an elliptical base, and to discriminate square from rectangular cuboids. Results show that the base ratio to perceive objects with curvature is smaller than the needed ratio to perceive cuboid differences, suggesting that curvature is a relevant cue in haptic experience, facilitating object perception.

According to Klatzky, Lederman, and Metzger (1985), this group of studies on touch, using abstract stimulation, might be contributing to an underestimation of haptic abilities. To these authors, a main distinction between abstract and everyday objects perception and recognition, rises from the concept of *pattern recognition. Everyday object's are perceived as patterns, analysed as a whole, while abstract stimuli are perceived as a sum of different features* (Klatzky & Lederman, 2003). They argue that haptic recognition of everyday objects entails an apprehension of tactile patterns that is achieved through both bottom-up and topdown processes, and these aspects differentiate haptic perception from simple categorisation that is typical in the perception of abstract stimuli (Klatzky et al., 1985).

Overall we can assume that experiments with two and three dimensional abstract stimuli, although useful to analyse haptic evaluation of specific properties, devoid haptics from crucial cues such as material properties (e.g., texture or weight information), conducting to an estimation of haptic ability that does not necessarily correspond to performance in optimal conditions.

3. TYPE OF STIMULI: CONCRETE STIMULI

3.1. Familiar and unfamiliar stimuli

Bülthoff and Newell (2006) present a thorough review on the role of familiarity in the perception of objects, faces, and movement. The authors conclude that stimuli familiarity is a central feature in perception and that people are more efficient responding to learned than unknown objects, which led the authors to assume that our perceptual system is organised through these familiar stimuli or events.

In fact, much research has been conducted exploring the role of familiarity in our perceptual and cognitive experience, and familiar objects, whether everyday stimuli or stimuli learned during the experimental session, seem to generate better performance from the participants than unfamiliar stimuli.

A study with children showed that, although they were very good at haptically recognising a list of 16 unfamiliar objects (e.g., segments of other objects), their performance was optimal in the familiar objects' set, with children being able to correctly recognise about 15 of the 16 presented objects (Bushnell & Baxt, 1990). Also Lacey and Campbell (2006), in a study with adults in a crossmodal visuo-haptic paradigm, report that participants are able to recognise between 15 and 16 objects in a 16 object set for familiar items and around 13 to 14 objects in unfamiliar objects trials. In two recent functional magnetic resonance studies (Lacey, Flueckiger, Stilla, Lava, & Sathian, 2010; Deshpande, Hu, Lacey, Stilla, & Sathian, 2010) the authors argue that crossmodal visuo-tactile interactions in the brain are modulated by the item's familiarity, when they found that the activation overlapping between haptic and visual trials was bigger for familiar than unfamiliar objects.

A series of studies has also shown that people have preferred "views" or perspectives to perceive objects by touch. These views are called *canonical views* and had been studied in vision, with people being more effective at recognising objects presented from a familiar perspective then when presented in a different orientation (Newell, Ernst, Tjan, & Bülthoff, 2001). Even in free exploration conditions, participants still prefer the haptic canonical view to manipulate objects and the hands favour a "back" perspective instead of the "front" perspective, typical of vision (Newell et al., 2001). Participants show coherence in the selection of haptic canonical views, either for familiar or unfamiliar stimuli, and these perspectives allow a better recognition performance (Woods, Moore, & Newell, 2008). The viewpoint dependency in touch is verified either for stimuli learned in the experimental task, either for everyday stimuli and is mediated by task difficulty, with the most difficult discrimination tasks being more impaired by changes in stimuli perspective (Lawson & Bullthoff, 2008). Even within the viewpoint or orientation procedures, differences can be found between familiar and unfamiliar objects (Craddock & Lawson, 2008), with objects' recognition being dependent on the orientation in which stimuli were presented, for both types of objects, but with larger errors for unfamiliar than for familiar objects.

Haptic recognition of familiar objects is also sensitive to size and shape changes (Craddock & Lawson, 2009b). In this study participants were asked to recognise objects based on identity and ignoring size or shape variations. Results showed that generalisation occurred in touch, but there was a cost, since participant's recognition performance was lightly impaired in trials in which a change was present.

Klatzky et al. (1985) had proven touch to be an effective and highly accurate system in the perception of familiar everyday objects, and had defined that people need about two to three seconds (sometimes less) to be able to identify a stimulus presented through touch only. A later work (Klatzky & Lederman, 1995) reveals that participants are able to identify familiar objects without any cues with presentations as short as 200 ms, with an accuracy level of 20%. When analysing the errors, the authors found that the most typical errors corresponded to identifications of other items similar to the target (e.g., identifying a pencil as a pen).

As reported in this brief review of the literature on haptic perception and recognition, performance with familiar objects is consistently better than with unfamiliar objects. Familiarity is, as such a central variable in haptic cognition, and the ability of the haptic system in recognition and perception of these type of stimuli must be explored, since it can provide valuable information to the understanding of haptic cognition.

3.2. Faces

The representation of faces has been considered distinct from the representation of other stimuli (Kanwisher, 2000). Most studies on face perception and recognition have been conducted within the visual modality (e.g., Bruce & Young, 1998) but in recent years the study of haptic facial recognition has produced interesting results. Kilgour and Lederman (2002) presented a study with three conditions: haptic study and recognition of live faces, haptic study and recognition of facial masks, and visuo-haptic study of live faces with haptic recognition. Results showed that participants were able to correctly identify unfamiliar faces by touch only with rates of about 80% for the first condition, about 70% in the second and about 60% in the last. The two last conditions, with haptic recognition of face masks, implied a loss of material cues of the stimuli and participants had to perform their evaluations based on geometrical cues only. Since material cues are central in haptic recognition (Klatzky, Lederman, & Reed, 1987), this is an expected result.

Also, people can recognise facial emotional expressions by touch only, whether touching face masks or people interpreting the emotional expression (Lederman et al., 2007). In the same study haptic recognition of emotional facial expressions was analysed comparing dynamic (expressions made by actors) and static (masks representing emotions) emotional faces. The hypothesis was that if participants can recognise the haptic and tactile inputs of an emotional face, they should be able to correctly identify the six universal expressions of emotion (Lederman et al., 2007). Results reveal that participants are better at recognising dynamic than static emotional expressions, and that happiness, sadness, and surprise are easier to recognise by touch than anger, disgust, and fear.

Casey and Newell (2005) investigated the familiarity in haptic recognition of faces, and concluded that participants were not able to haptically recognised their own face, although the task was facilitated by visual priming of their live face. In a second experiment, the authors reported that familiarisation with a group of unknown faces improved crossmodal recognition (Casey & Newell, 2005). In a later study (Casey & Newell, 2007), the authors conclude that face representations are modality specific, although configurational properties of the faces seemed to be shared between vision and touch (in opposition to feature information).

The relevance of familiarity in face perception has also been pointed out by Bülthoff and Newell (2006), arguing that familiarity is a central process in human perception and that familiar stimuli always present better learning and recognition performance.

The haptic system appears to be a valuable perceptual resource, presenting surprisingly good performance even in tasks that are not familiar or recurrent in everyday experience, such as recognising a face or identifying an emotional expressions through touch only.

4. TYPE OF PARTICIPANTS

4.1. Blind participants

Historically the study of touch and blindness has roots in philosophy, medicine and psychology. The idea of enhanced tactile and auditory perception in blind subjects (e.g., Cattaneo & Vecchi, 2011), and the notion of sensory substitution (e.g., Bach-y-Rita, 1972) are very present in literature. However, research shows that information from different sensory modalities is not always easily interchangeable (e.g., Röder & Rösler, 2004).

Authors have considered the study of haptic perception with blind participants as relevant because studies with blindfolded sighted participants might be resulting in an underestimation of haptic abilities (Heller & Ballesteros, 2006). Research with blind participants has suggested that they have better performance in haptic tasks than sighted participants (e.g., Postma, Zuidhoek, Noordzij, & Kappers, 2007), But this advantage is not always present (e.g., Alary et al., 2009).

Many authors have emphasised the role of practice in performance for touch (e.g., (Cohen, Scherzer, Viau, Voss, & Lepore, 2011), and within this perspective one must consider that blind participants have a larger experience in perceiving objects mainly by touch than sighted participants, and this familiarisation might be modulating the results, at least for experiments in which the stimuli are common or familiar stimuli.

However, Abramowicz, Klatzky, and Lederman (2010) have shown that with the presentation of highly unfamiliar and uncommon stimuli, blind and sighted participants show equivalent learning rates. In this study, the authors showed that it was possible to perceive emotional facial expression through schematic raised line drawings. Another central conclusion of this study, was that blind participants can be trained to detect emotional facial expressions. Also, in a study comparing performance in haptic recognition of two dimensional patterns, with early blind, late-blind and sighted participants, it was reported that the three groups presented similar rates of performance, although particpants were reporting different memory strategies when encoding the stimuli (Picard, Lebaz, Jouffrais, & Monnier, 2010).

The comparison of blind and sighted participants in an angle discrimination task showed better performance of the blind participants' group (Alary et al., 2008). Participants had to touch two dimensional angles with one finger and evaluate which one was the largest. Blind participants consistently revealed lower thresholds for angle discrimination. In a later study (Alary et al., 2009) the authors aimed to generalise this finding to other discrimination tasks and reported that the blind participants advantage is not task independent. In this study, there were no differences between the groups (composed by the same participants who collaborated in the earlier study) in haptic perception for a grating orientation task, and for a vibrotactile frequency task. However, blind participants performed better in a discrimination of texture task, fact that the authors attribute to the possible similarity between the presented dotted textures and braille characters.

Blind participants have shown faster performance in shape correspondence tasks (Postma et al., 2007). In this study, in a speeded task in which participants were asked to match shapes to their negative in a board as fast as possible, the blind participants group was faster, but not more accurate than the sighted participants group. However, in a non-speeded task, no differences were revealed between the two groups.

In a study on haptic concepts (Homa, Kahol, Tripathi, Bratton, & Panchanathan, 2009) four groups (blind participants, sighted blindfolded participants, sighted and touching participants and sighted only participants) were asked to perform classification and recognition tasks with a set of objects varying on texture, shape and size. Results revealed that all participants took approximately the same amount of time to learn the categories. However, blind participants differed from the other groups by presenting less false alarms to new patterns that belonged to the category, and revealing more false alarms to the category prototype, which was falsely recalled in all trials.

Stevens, Foulke, and Patterson (1996) show that tactile acuity decreases as a function of age at the same rhythm for sighted and blind participants, resulting in slower Braille reading in the blind participants' group.

Equivalence from spatial processing in vision and touch has also been reported in research with blind participants. For instance, learning of maps through vision in sighted participants or through touch in blind participants revealed similar patterns, showing that haptic information does not need to be translated into visual codes, having direct access to spatial processing (Giudice et al., 2011).

Another interesting group of results reports the existence of visual imagery in blind participants, questioning the notion that imagery is visual in nature, and suggesting the existence of shared components between vision and haptics. In 1983, a research report reveals that blind and sighted adults and children showed equivalent performance in three imagery memory tasks (Zimler & Keenan, 1985). In the first experiment participants were asked to recall paired associated words that were high in either visual or auditory imagery and all participants recalled more visual imagery words. The second experiment consisted in the recall of list of words associated by modality-specific features, as colour or sound and all participants reported more words on the colour lists than on the sound lists. In a final experiment, the authors were able to replicate the visual occlusion effect with haptic pictures presented to blind participants.

Pring and Rusted (1985) showed that blind children could benefit as much from haptic pictures as sighted children benefit of visual pictures in educational settings. Children either hear a description of a rare animal or haptically explored a picture of the animal and results showed that children in the second condition were able to remember more information about the animals.

Cornoldi, De Beni, Giusberti, and Massironi (1998) consider that mental imagery has to be understood as a group of complex processes that generate representations, and not only as a perceptual trace. From this point of view, mental images do no need to be visual in nature and can be elicited by other sensory modalities.

The previously presented studies are a sample of a vast literature on haptic perception with blind participants. These research reports allow the clarification of some concepts and allow a better understanding of how the brain works and adjusts to sensory deprivation. Studies with blind subjects make it possible to conceive a scheme of the brain where perception is not dominated by vision, and in which other sensory modalities processes can be explained without the need to hypothesise the conversion of information to visual codes, even when we are talking about mental images.

Overall, some studies with blind participants have suggested advantages in haptic perception when compared to sighted participants (e.g. Heller & Ballesteros, 2006). Nonetheless, the role of experience and familiarity has to be considered in our interpretations, and performance of blind and sighted subjects in conditions that are novel for both groups, as well as conditions that are highly familiar to both, seems to be greatly equivalent.

4.2. Children

A developmental approach to touch is interesting to understand how human perception evolves through life span and can also provide some insight into how information acquired by touch is processed and weighted at different ages.

Studies with very young children (before the development of language) are relevant because they allow access to truly perceptual tactile features, since young children are not capable of semantically or verbally encode or rehearse the stimuli (Gallace & Spence, 2009).There are some studies regarding touch in newborns and infants, mainly recurring to the novelty paradigm. This paradigm is based on the conclusion that babies tend to be attracted by new stimuli, and was designed over this assumption, evaluating if a child looks at a stimulus as new by the time spent exploring it. Longer exploration times indicate the stimuli is being perceived as new. With the novelty paradigm, the existence of some form of tactile memory has been reported in children as young as two-month old (Lhote & Streri, 1998), and even newborns are capable of detecting changes in two stimuli with either hand (Streri, Lhote, & Dutilleul, 2000). Also Catherwood (1993) in a study with infants with about eight-months of age, showed retention of tactile information for both shape and texture with immediate recognition, for shape and to lesser extent texture after a delay, and only for texture in interference conditions.

Corbetta and Snapp-Childs (2009) highlight the role of touch in early development, considering that coordination between touch and vision is crucial to maintain an interaction with the surrounding stimuli, and try to analyse the relative weight of tactile and visual experience in the modulation of grasping, reaching and other object oriented motor responses of six to nine months old children. Results show that younger children do not adapt their movements according to previous experience with the stimuli, but older children do, relying first on touch information, and later more in visual cues to match their movements to the specific objects, based on previous experience with them (Corbetta & Snapp-Childs, 2009).

Bigelow (1981), presents a study with two groups of children, one with children around two and a half years old and the other with children of five years old, and asked them to haptically identify miniatures of small objects (e.g., doll's spoon), miniatures of large objects (e.g., doll's sofa), and small objects in real size (e.g., key.) Older children were better than younger children in all conditions, and the two children groups were better at identifying small objects in real size than either of the two other object sets. Curiously, the younger children were able to identify more small miniaturised objects than large miniaturised objects, a pattern that was not observed in older children. The author concludes that younger children have more difficulty in haptically perceive and explore objects they cannot comprise in real size, and the greater difficulty in identifying the miniatures of large objects was a consequence of lack of experience of haptic exploration of the objects in real life. As for the older children, their crossmodal abilities are more developed and they were able to identify the objects by translating the visual information from real life to an haptic information. Bushnell and Baxt (1990) in a recognition study with familiar and unfamiliar objects with a group of five year-old children report a "remarkably good" haptic memory, nearly perfect for familiar objects and excellent for unfamiliar objects as well.

The exploratory procedures of children up to 11 years-old does not seem to be strictly object or property dependent (Hatwell, 2003), with children performing the same movements, independently of the given instruction, while adults adjust the exploratory procedures both to object and task specificity. Haptic perception relies highly on movements and intentional exploration, and as such is dependent on the development of the motor system, likewise, the development of cognitive abilities like working memory is important to adjust, maintain and bind acquired information that allows haptic perception and motor optimisation of the manipulation procedures (Hatwell, 2003).

Children show the ability to retain haptic specific information from birth, and initially use mainly motor and haptic features to guide objects exploration. However, accuracy in haptic recognition of unfamiliar items, and the ability to adjust exploration procedures seems to develop later.

4.3. Sex differences

Literature on touch and sex differences appears mainly in social and interpersonal research, analysing touch as a form of communication (e.g., Gallace & Spence, 2010; Jones, 1986; Stier & Hall, 1984; Willis & Hofmann, 1975). However, other studies have explored sex differences in touch within experimental tasks.

Bardwick (1971) presents a review of studies about tactile perception in girls and women, and concludes that the evidence for sex differences is scarce and incongruent, and for that reason argues in favour of assuming no differences in performance. Researches have discarded sex differences analysis from their works, and research on haptic perception has focused in establishing general rules of processing, regardless of the participants' sex. However, some studies can be identified in which sex differences are reported.

Heller et al. (2010) explores differences between women and men in a study in which participants had to detected changes of position in raised line drawings presented in a matrix. Results reveal that female participants present better results than male participants, but these differences disappear in more difficult tasks. Overall, the reported sex difference was small and congruent with the differences found in vision for a similar task.

Analyzing the perception of tactile simultaneity of pairs of stimuli, Geffen, Rosa, & Luciano (2000a; 2000b) did not result in consistent sex differences between participants, reporting that male performance was faster, but not in all conditions.

Using positron emission topography, Sadato, Ibañez, Deiber, and Hallett (2000) describe differences between men and women in the activation of the dorsal premotor cortex, which was asymmetrical in men, but symmetrical in women. The authors conclude that this might suggest differences between the groups in tasks such as discrimination through active touch, where interhemispheric connection would be stronger in women.

In haptic orientation perception, differences were found between male and female participants (Zuidhoek, Kappers, & Postma, 2007). In this study participants were distributed through three experiments, in which they were asked to either touch a plastic bar with one hand and orient another plastic bar with the other hand in a way that both bars were parallel; use just one hand and provide a verbal answer, considering the bar as a pointer in a clock, and identifying the minutes it represented for each orientation; or orient a bar such as a clock pointer according to the indication of the experimenter. Results showed that males were more accurate in parallel setting and haptic orientation perception.

Although there are some studies reporting differences between male and female participants in some specific haptic tasks, this variable has not been part of most systematic studies on touch. Moreover, experimental results of sex differences manipulations are not very clear, usually presenting small or inconsistent effects.

5. TYPE OF STIMULI EXPLORATION

5.1. Passive and Active Touch

In touch research, three main types of touch are distinguished: *passive touch*, *active touch* and *dynamic touch*. Passive touch refers to conditions in which participants are not allowed to move and the stimuli are presented against the skin. This type of touch is used with airjets (e.g., Bliss, Crane, & Mansfield, 1966), vibration (e.g., Gallace, Tan, Haggard, & Spence, 2008), or even by pressing still stimuli against the participant's skin (e.g., Cronin, 1977). Active touch implies movement from the participants and can be: 1) free, when the participants are allowed to explore the objects with the whole hand (e.g., Klatzky et al., 1985), or 2) restricted, when participants can touch the objects 2.1) with only one finger (e.g., Klatzky & Lederman, 1995), 2.2) through gloves (e.g., Klatzky, Loomis, Lederman, Wake, & Fujita, 1993), or 2.3) with a specific type of movement (e.g., Lederman & Klatzky, 2004). Dynamic touch was defined by Gibson (1966) as the perception that results from the combination of cutaneous, muscular and joints cues. Experimentally, dynamic touch is a condition that allows higher experimental control than active touch, since participants are not allowed to move their hands, minimising variations in exploration. In such conditions the stimuli are moved through the participant's skin, allowing the perception of movement cues not present in passive touch, but not requiring the voluntary exploration present in active touch (e.g., Turvey, 1996; Sanders & Kappers, 2008). This type of touch is sometimes reffered to as an option of passive touch, in which the stimuli are moved by the experimenter (e.g., Cronin, 1977), or by a mechanical device, against the participant's skin allowing the participant to perceive relevant cues that result from movement, without having to actively manipulate the stimuli.

Gibson (1962) in an analysis of active touch, emphasises the exploratory nature of active touch, in contrast to the receptive nature of passive touch, which is caused by an external agent. Moreover, Gibson (1962) argues that active touch is not equivalent to a simple adding of passive touch and kinaesthesia.

Cronin (1977) analyses the differences between active and passive touch in the identification of geometrical forms. Comparing participants in the first, third and fifth grade and college students, the author concludes that a developmental advantage exists for active touch (the participants actively touch the object) and dynamic touch (the stimulus is moved against the participant's hand) conditions, but not for passive touch conditions, in which first year participants showed differences compared to the college students, but not to third and fifth year students. The author argues that the equivalence in performance between active and dynamic touch might be explained by the fact that participants had to explore the objects with the palm of the hand, and not the finger, which could have limited the type of information gathered in active touch conditions, making it similar to dynamic touch. Overall, conditions that involved movement resulted in better performance than passive touch, in every age group.

In a study comparing the perception of forms in active and passive exploration conditions (Heller, 1984), results also pointed to a clear advantage of active touch, with passive static or sequential presentation resulting in worst identification than active touch.

However, in some conditions passive touch might present an advantage when compared to active touch (e.g., Richardson, Wuillemin, & Mackintosh, 2011) or there can be conditions where active touch shows no advantage in performance (e.g., Güçlü & Morat, 2007). In a recent study comparing tactile learning of a maze (Richardson et al., 2011), participants in the passive touch condition were must faster to learn the path than participants in the active touch condition. Nonetheless, the disadvantage in the active conditions was due to the repetition of errors in the chosen paths and was a consequence of the participants' decisions. As such, the authors conclude that the active touch disadvantage translated a cognitive limitation and not a haptic system limitation (Richardson et al., 2011). Guçlu and Morat (2007) published a study comparing active and passive touch in a counting task. Participants had to count the number of bumps presented in sticks that were either actively explored or slid against the participants' hands. Results showed that active touch did not imply a better performance.

Active and passive touch are distinct processes. While active touch involves proprioception, kinaesthesia and cutaneous senses, passive touch relies only on the last. Interestingly, electrophysiology studies have reported that active touch generates a suppression of afferent information to the somatosensory cortex, a phenomenon known as *movement related sensory gating* (e.g., Chapman, 1994). This phenomenon could lead to worst encoding in active than passive touch. However active touch allows the participant to control movement velocity and to select which properties to evaluate at each moment, resulting in a central advantage for active touch (Chapman, 1994).

Using functional Magnetic Resonance Image (fMRI) in a study that required evaluation of roughness in active (participants moved their fingers through the samples) and passive (the samples were moved beneath the participants' fingers) touch, it was possible to verify that exploratory condition affected activation in the primary sensory cortex, and that active touch resulted in a larger pattern of activation, possibly because of the motor component of this condition (Simões-Franklin, Whitaker, & Newell, 2011).

Although considering some exceptions to the active touch superiority, it seems that this type of stimuli exploration in touch is ideal to observe optimal performance. As Gibson (1962) argued many years ago, it is possible to explore active perception in touch as it is to explore passive perception, and active touch seems to be able to provide more information about processing in touch.

5.2. Relevance of Movement in Touch

The relevance of movement in touch was valued since the first efforts to systematically study this modality. Gibson (1966), Katz (1925/1989) and Weber (1834/1996 and 1905/1996), understood the relevance of dynamic contact with the stimuli from their early experiments and considered the sense of movement crucial in tactile perception. Later, the works of Lederman and Klatzky (e.g., Lederman & Klatzky, 1996) brought a first effort to give some structure to our knowledge about movement in touch. Nonetheless, despite the importance of movement to touch, most studies with tactile stimuli are still conducted with passive stimulation (e.g., Spence & Gallace, 2007). In fact, the variability of hand movements that people perform to explore an object presented by touch only, makes it harder to control for exploration times and inter-stimulus interval and introduces some individual variability in the way stimuli are explored, although general movement patterns are detectable (Lederman & Klatzky, 1987).

Movement is determinant for overall object manipulation, specially the acquisition of some object properties like texture, shape, weight, or volume. Movement is also pertinent to the perception of objects in space (Kaas et al., 2008) and grasping has been shown to be a crucial stage in object identification (Klatzky, 1992).

Lederman and Klatzky (1987) provided a systematic classification of manual object exploration. In this study participants were asked to touch everyday objects, without sight, and to evaluate a specific features like *weight*. Participants were allowed to explore the objects freely with both hands. Through a complex movement analysis, that involved video examinations by naive evaluators, the authors were able to discriminate between six essential movement patterns, each one specified in collecting particular information from the objects: lateral motion (texture), pressure (hardness), static contact (temperature), unsupported holding (weight), enclosure (volume, global shape), and contour following (exact shape). Lederman and Klatzky (1987) called these movement patterns *exploratory procedures* and defined them as *a stereotyped movement pattern having certain characteristics that are variant and others that are highly typical*. By this definition the authors explained that it is possible to identify general patterns of movement, equivalent in all participants (for instance rubbing an object to evaluate its texture), although there are some variations in the individual exploration (for instance, some participants rub the object with only one finger while other might use two fingers or even the whole hand).

More recently, using a movement tracking device, Kappers (Kappers & Douw, 2010; Tiest, Norman, Kahrimanovic, & Kappers, 2010) initiated research on the relevance of movements while exploring two dimensional stimuli. Tiest et al. (2010) were able to extract specific patterns of exploration from the movement coordinates recorded through the experiment and were able to establish relations between these patterns and specific properties evaluations, namely hardness, coldness, texture, and texture orientation. Kappers and Douw (2010) work revealed that participants perform the same type of movements when trying to answer to the same questions exploring a stimuli matrix (e.g., *Which sample is the warmest)?*. These studies show that haptic movements are specific and directed to feature evaluation, and that the movement patterns noted by Lederman and Klatzky (1987) regarding three-dimensional everyday objects also emerge with to two-dimensional stimuli, although the movements that characterise each pattern might suffer some alteration due to stimuli specificity (e.g., global shape and shape contours correspond to the same procedure for two-dimensional objects, since participants can not hold these type of stimuli).

5.3. Exploratory movements and time

Haptic processing is sequential (Loomis, Klatzky, & Lederman, 1991) which means that we can only process a small amount of information about the stimuli at one time. The consequence of this type of processing is that haptic exploration takes longer times. Vision, on the other hand, presents a parallel processing, being able to collect simultaneously a set of different properties from the stimuli. In an experiment designed to compare visual and haptic processing in sequential processing Loomis et al. (1991) restricted the visual field of view in object exploration, allowing the participants to look sequentially to a small area in different points of a stimulus. Within these conditions, performance was very similar in haptic and visual perception, revealing that the type of processing significantly affected the participants' ability to recognise stimuli. This distinction is crucial and when planning haptic experiments one should allow suficient time for haptic stimuli exploration.

Freides (1974) reviewing literature on sensory modality effects, alerts to the differences in time resolution between sensory modalities. Goodnow (1971) observed that when delays increased, shape matching in touch was much more affected than in vision. Also Wagner and Sakovits (1986) indicated that vision was capable of processing more information than touch within the same time.

Lacey and Campbell (2006) report that the ratio in presentation times has to be of 2:1 when comparing haptic to visual presentation, a conclusion they came across during a series of pilot experiments. Woods, O'Modhrain and Newell (2004) report that matching performance levels in a crossmodal paradigm with vision and touch, implied that stimuli presentation in touch took twice the time of the visual presentation. Likewise, in a study with three-dimensional complex objects, built with toy construction blocks, it was found that visual presentation required half the time as haptic presentation (Newell et al., 2001).

Time is a crucial variable in memory, and our ability to maintain a certain stimulus in memory actually contributes to the definition of that specific memory storage. As such, in haptic experiments, if the participants are taking longer to perceive the stimuli, they will take longer to perform the task, which can result in a need to establish specific durations of haptic memory stores. Furthermore, the increased presentation times in haptics make comparison with vision and audition very difficult in traditional memory paradigms, such as memory span or even n-back tasks. Although a direct comparison between performance in all sensory modalities in similar tasks might not be possible, it is necessary to explore haptic memory attending to its specificity and maybe comparing haptic performance in optimal haptic conditions in contrast with general conditions in which other modalities have been evaluated. In this context, analysing visual and auditory tasks with equivalent times to haptic optimal performance might enlighten how haptic information is processed and clarify if haptic memory storages present longer durations than visual or auditory stores.

6. CONCLUSION

This section of our review aimed to classify previous studies on touch according to their methodology. We evaluated the way different variables affect results in touch experiments, and pondered the consequences of these manipulations for memory experiments. As such, we analysed: 1) interaction with touch and other senses; 2) the impact of the type of stimuli (concrete and abstract); 3) the type of participants; and 4) the type of stimuli exploration that is adopted. A systematic approach of the implications of these variables was not present in the literature and provides a general introduction to all the specific variations that one must consider when designing experiments on touch.

Performance in touch experiments seems to be highly variable, and it is important to focus on each variable that might be contributing to those seemingly incongruent results in haptic performance. Further knowledge on touch has to consider all the possible influences in touch performance.

The conditions in which touch is evaluated determine our understanding of this sensory modality and limit the interpretation and possible generalisation of results. The target stimuli of an experiment (patterns, familiar objects, uncommon shapes, complex matrices, etc.), the presentation conditions (serial or parallel, through active or passive touch), as well as the chosen participant sample (children, younger adults, older adults, healthy participants, mild cognitive impaired participants, blind participants, etc.), should be attended and considered when trying to generalise research results and draw implications to theoretical perspectives.

The nature of the presented stimuli, the understanding of the specificities of the participants group in the experiment, and the conditions in which manual exploration is allowed are central variables in the study of touch and will be explored and clarified in throughout this section. All of these variables contribute to the understanding of differences and similarities between touch and other sensory modalities, as well as to the exploration of the existence of amodal or modality independent processing modes that allow exchange of information between sensory modalities.

REFERENCES

Abramowicz, A., Klatzky, R.L., & Lederman, S.J. (2010). Learning and generalization in haptic classification of 2-D raised-line drawings of facial expressions of emotion by sighted and adventitiously blind observers *Perception*, *39*(9), 1261–1275. doi:10.1068/p6686

Alary, F., Goldstein, R., Duquette, M., Chapman, C.E., Voss, P., & Lepore, F. (2008). Tactile acuity in the blind: a psychophysical study using a two-dimensional angle discrimination task. *Experimental Brain Research*, *187*(4), 587–594. doi:10.1007/s00221-008-1327-7

Alary, F., Duquette, M., Goldstein, R., Chapman, C.E., Voss, P., La Buissonnière-Ariza, V., & Lepore, F. (2009). Tactile acuity in the blind: A closer look reveals superiority over the sighted in some but not all cutaneous tasks. *Neuropsychologia*, *47*(10), 2037–2043. doi:10.1016/j.neuropsychologia.2009.03.014

Auvray, M., & Spence, C. (2008). The multisensory perception of flavor. *Conscious Cognition*, *17*(3), 1016–1031. doi: 10.1016/j.concog.2007.06.005

Auvray, M., Gallace, A., Tan, H. Z., & Spence, C. (2007). Crossmodal change blindness between vision and touch. *Acta Psychologica (Amst)*, *126* (2), 79–97. doi:10.1016/j.actpsy.2006.10.005

Bach-y-Rita, P. (1972). *Brain mechanisms in sensory substitution*. New York: Academic Press.

Ballesteros, S., & Heller, M.A. (2008). Haptic object identification. In M. Grünwald (Ed.), *Human Haptic Perception: Basics and Applications* (pp. 207–222). Basel: Birkhäuser

Ballesteros, S., Manga, D., & Reales, J.M. (1997). Haptic discrimination of bilateral symmetry in 2-dimensional and 3-dimensional unfamiliar displays. *Perception & Psychophysics*, *59*(1), 37–50.

Bancroft, T., & Servos, P. (2011). Distractor frequency influences performance in vibrotactile working memory *Experimental Brain Research*, *208*(4), 529–532. doi:10.1007/s00221-010-2501-2

Bardwick, J. (1971). *Psychology of women*. Michigan: Harper & Row

Bigelow, A. (1981). Children's tactile identification of miniaturized common objects *Developmental Psychology*, *17*(1), pp. 111-114

Bliss, J., Crane, H., & Mansfield, P. (1966). Information available in brief tactile presentations. *Perception & Psychophysics*, *1*, pp. 273-283.

Bresciani, J., Ernst, M., Drewing, K., Bouyer, G., Maury, V., & Kheddar, A. (2005). Feeling what you hear: auditory signals can modulate tactile tap perception. *Experimental Brain Research*, *162*(2), 172–180. doi:10.1007/s00221-004-2128-2

Bresciani, J.-P., & Ernst, M.O. (2007). Signal reliability modulates auditory-tactile integration for event counting. *Neuroreport*, *18*(11), 1157–1161. doi:10.1097/WNR.0b013e3281ace0ca

Bruce, V., & Young, A. (1998). *In the eye of the beholder: The science of face perception.* New York: Oxford University Press.

Bruns, P., & Röder, B. (2010). Tactile capture of auditory localization: an event-related potential study. *The European journal of neuroscience*, *31*(10), 1844–1857. doi:10.1111/j.1460-9568.2010.07232.x

Bult, J.H.F., de Wijk, R.A., & Hummel, T. (2007). Investigations on multimodal sensory integration: Texture, taste, and ortho- and retronasal olfactory stimuli in concert. *Neuroscience Letters*, *411*(1), 6–10. doi:10.1016/j.neulet.2006.09.036

Bushnell, E.W., & Baxt, C. (1990). Children's Haptic and Cross-Modal Recognition With Familiar and Unfamiliar Objects. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(6), 1867–1881.

Bülthoff, I., & Newell, F.N. (2006). The role of familiarity in the recognition of static and dynamic objects. *Prog Brain Res*, *154*, 315–325. doi:10.1016/S0079-6123(06)54017-8

Casey, S.J., & Newell, F.N. (2005). The role of long-term and short-term familiarity in visual and haptic face recognition. *Experimental Brain Research*, *166*(3-4), 583–591. doi:10.1007/s00221-005-2398-3

Casey, S.J., & Newell, F.N. (2007). Are representations of unfamiliar faces independent of encoding modality *Neuropsychologia*, *45*(3), 506–513. doi:10.1016/j.neuropsychologia.2006.02.011

Catherwood, D. (1993). The robustness of infant haptic memory: Testing its capacity to withstand delay and haptic interference. *Child development*, *64*, pp. 702-710.

Cattaneo, Z., & Vecchi, T. (2008). Supramodality effects in visual and haptic spatial processes *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*(3), 631–642. doi:10.1037/0278-7393.34.3.631

Cattaneo, Z., & Vecchi, T. (2011). *Blind Vision: The neuroscience of visual impairment.* London: MIT Press.

Chapman, C.E. (1994). Active versus passive touch: factors influencing the transmission of somatosensory signals to primary somatosensory cortex. *Canadian Journal of Physiology and Pharmacology*, *72*(5), 558–570. NRC Research Press Ottawa, Canada. doi:10.1139/y94-080

Cholewiak, R.W., Collins, A.A., & Brill, C. (2001). Spatial Factors in Vibrotactile Pattern Perception. In: Proceedings Eurohaptics 2001, July 1-4, 2001, Birmingham, UK.

Cinel, C., Humphreys, G.W., & Poli, R. (2002). Cross-modal illusory conjunctions between vision and touch *Journal of Experimental Psychology: Human Perception and Performance*, *28*(5), 1243–1266. doi: 10.1037//0096-1523.28.5.1243

Cohen, H., Scherzer, P., Viau, R., Voss, P., & Lepore, F. (2011). Working memory for braille is shaped by experience *Communicative & integrative biology*, *4*(2), 227–229. doi:10.4161/cib.4.2.14546

Corbetta, D., & Snapp-Childs, W. (2009). Seeing and touching: the role of sensory-motor experience on the development of infant reaching. *Infant Behav Dev*, *32*(1), 44–58. doi:10.1016/j.infbeh.2008.10.004

Cornoldi, C., De Beni, R., Giusberti, F., & Massironi, M. (1998). Memory and imagery: A visual trace is not a mental image. In M. Conway, S. Gathercole, & C. Cornoldi (Eds.), *Theories of Memory* (Vol. 2, pp. 87–110). Hove: Psychology Press.

Craddock, M., & Lawson, R. (2008). Repetition priming and the haptic recognition of familiar and unfamiliar objects. *Perception & Psychophysics*, *70*(7), 1350–1365. doi:10.3758/PP.70.7.1350

Craddock, M., & Lawson, R. (2009a). Size-Sensitive Perceptual Representations Underlie Visual and Haptic Object Recognition. *PLoS ONE*, *4*(11), –. doi:10.1371/journal.pone.0008009

Craddock, M., & Lawson, R. (2009b). The effects of size changes on haptic object recognition *Attention, Perception, & Psychophysics*, *71*(4), 910–923. doi:10.3758/APP.71.4.910

Craig, J., & Evans, P. (1987). Vibrotactile masking and the persistence of tactual features *Perception & Psychophysics*, *42*(4), 309–317.

Cronin, V. (1977). Active and passive touch at four age levels *Developmental Psychology*, *13*(3), 253–256.

Cruz, A., & Green, B.G. (2000). Thermal stimulation of taste *Nature*, *403*(6772), 889–892. doi:10.1038/35002581

Delwiche, J. (2004). The impact of perceptual interactions on perceived flavor. *Food Quality and Preference*, *15*(2), 137–146. doi:10.1016/S0950-3293(03)00041-7

Demattè, M.L., Sanabria, D., Sugarman, R., & Spence, C. (2006). Cross-modal interactions between olfaction and touch. *Chem Senses*, *31*(4), 291–300. doi:10.1093/chemse/bjj031

Deshpande, G., Hu, X., Lacey, S., Stilla, R., & Sathian, K. (2010). Object familiarity modulates effective connectivity during haptic shape perception. *NeuroImage*, *49*(3), 1991–2000. Elsevier B.V. doi:10.1016/j.neuroimage.2009.08.052

Easton, R., Greene, A., & Srinivas, K. (1997). Transfer between vision and haptics: Memory for 2-D patterns and 3-D objects. *Psychonomic Bulletin & Review*, *4*(3), pp. 403-410.

Easton, R., Srinivas, K., & Greene, A. (1997). Do vision and haptics share common representations? Implicit and explicit memory within and between modalities. *Journal of Experimental Psychology: Learning, Memory and Cognition, 23,* pp. 153-163.

Ernst, M.O., & Banks, M.S. (2002). Humans integrate visual and haptic information in a statistically optimal fashion *Nature*, *415*(6870), 429–433. doi:10.1038/415429a

Freides, D. (1974). Human information processing and sensory modality: cross-modal functions, information complexity, memory, and deficit *Psychological Bulletin*, *81*(5), 284–310.

Gallace, A., & Spence, C. (2009). The Cognitive and Neural Correlates of Tactile Memory. *Psychological Bulletin*, *135*(3), 380–406. doi:10.1037/a0015325

Gallace, A., & Spence, C. (2010). The science of interpersonal touch: An overview. *Neuroscience & Biobehavioral Reviews*, *34*(2), 246–259. doi:10.1016/j.neubiorev.2008.10.004

Gallace, A., Tan, H.Z., Haggard, P., & Spence, C. (2008). Short term memory for tactile stimuli. *Brain Research*, *1190*, 132–142. doi:10.1016/j.brainres.2007.11.014

Garbin, C.P. (1988). Visual-haptic perceptual nonequivalence for shape information and its impact upon cross-modal performance *Journal of Experimental Psychology: Human Perception and Performance*, *14*(4), 547–553.

Geffen, G., Rosa, V., & Luciano, M. (2000a). Effects of preferred hand and sex on the perception of tactile simultaneity. *Journal of Clinical and Experimental Neuropsychology*, *22*(2), 219–231.

Geffen, G., Rosa, V., & Luciano, M. (2000b). Sex differences in the perception of tactile simultaneity. *Cortex*, *36*(3), 323–335.

Gibson, J. (1966). *The senses considered as perceptual systems.* Oxford: Houghton Mifflin

Gibson, J.J. (1962). Observations on active touch *Psychological Review*, *69*(6), 477–491. American Psychological Association. doi:10.1037/h0046962

Gillmeister, H., & Eimer, M. (2007). Tactile enhancement of auditory detection and perceived loudness. *Brain Res*, *1160*, 58–68. doi:10.1016/j.brainres.2007.03.041

Giudice, N.A., Betty, M. R., & Loomis, J.M. (2011). Functional equivalence of spatial images from touch and vision: Evidence from spatial updating in blind and sighted individuals *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *37*(3), 621–634. doi:10.1037/a0022331

Goodnow, J.J. (1971). Eye and hand: differential memory and its effect on matching *Neuropsychologia*, *9*(1), 89–95.

Guclu, B. & Murat, A. (2007). Active touch does not improve sequential processing in a counting task. *Acta Neurobiologiae Experimentalis*, *67,* pp. 165-169.

Hagander, L., Midani, H., Kuskowski, M., & Parry, G. (2000). Quantitative sensory testing: effect of site and pressure on vibration thresholds. *Clinical neurophysiology*, *111*(6), 1066–1069.

Hatwell, Y. (2003). Manual exploratory procedures in children and adults. In Y. Hatwell, A. Streri, & E. Gentaz (Eds.), *Touching for Knowing*. Philadelphia: John Benjamins Publishing Company.

Helbig, H.B., & Ernst, M.O. (2008). Haptic perception in interaction with other senses. In M. Grünwald (Ed.), *Human Haptic Perception: Basics and Applications* (pp. 235–249). Basel: Birkhäuser Basel. doi: 10.1007/978-3-7643-7612-3_18

Heller, M. (1984). Active and passive touch: the influence of exp... [J Gen Psychol. 1984] - PubMed - NCBI. *The Journal of general psychology*.

Heller, M.A., Jones, M.L., Walk, A M., Schnarr, R., Hasara, A., & Litwiller, B. (2010). Sex differences in the haptic change task *The Journal of general psychology*, *137*(1), 49–62.

Heller, M., & Ballesteros, S. (2006). Preface. In M. Heller & S. Ballesteros (Eds.), *Touch and blindness: psychology and neuroscience*. New Jersey: Lawrence Erlbaum Associates.

Ho, C., Tan, H.Z., & Spence, C. (2006). The differential effect of vibrotactile and auditory cues on visual spatial attention. *Ergonomics*, *49*(7), 724–738. doi:10.1080/00140130600589887

Homa, D., Kahol, K., Tripathi, P., Bratton, L., & Panchanathan, S. (2009). Haptic concepts in the blind. *Attention, Perception, & Psychophysics*, *71*(4), 690–698. doi:10.3758/APP.71.4.690

Hötting, K., & Röder, B. (2004). Hearing cheats touch, but less in congenitally blind than in sighted individuals *Psychol Sci*, *15*(1), 60–64.

James, T.W., & Blake, R. (2004). Perceiving object motion using vision and touch. *Cogn Affect Behav Neurosci*, *4*(2), 201–207.

Jones, S.E. (1986). Sex differences in touch communication *Western Journal of Speech Communication*. Taylor & Francis.

Kaas, A., Stoeckel, M., & Goebel, R. (2008). The neural bases of haptic working memory. In M. Grunwald (Ed.), *Human haptic perception: Basics and applications* (pp. 113–129). Basel: Birkhäuser.

Kanwisher, N. (2000). Domain specificity in face perception. *Nature neuroscience*, *3*(8), pp. 759-763.

Kappers, A.M.L. & Douw, F. (2010). Hand movement investigations inspired by Yarbus. *Perception*, 39. Supplement ECVP Conference Abstracts, p.67.

Kappers, A.M.L., & Schakel, W.B. (2011). Comparison of the haptic and visual deviations in a parallelity task *Experimental Brain Research*, *208*(3), 467–473. doi:10.1007/s00221-010-2500-3

Katz, D. (1989). *The world of touch* (L. Krueger, Trans.). Hillsdale: Lawrence Erlbaum. (original work published in 1925).

Kilgour, A., & Lederman, S.J. (2002). Face Recognition by Hand. *Perception & Psychophysics*, *64*(3), 339–352. doi: 10.3758/BF03194708

Kiphart, M.J., Auday, B.C., & Cross, H.A. (1988). Short-term haptic memory for three-dimensional objects. *Perceptual and motor skills*, *66*(1), 79–91.

Kiphart, M.J., Hughes, J., Simmons, J., & Cross, H.A. (1992). Short-term haptic memory for complex objects. *Bulletin of the Psychonomic Society*, *30*(3), 212–214.

Klatzky, R.L., & Lederman, S.J. (2003). The Haptic Identification of Everyday Life Objects. In Y. Hatwell, A. Streri, & E. Gentaz (Eds.), *Touching for Knowing*. Philadelphia: John Benjamins Publishing Company.

Klatzky, R.L. (1992). Stages of manual exploration in haptic object identification. *Perception & Psychophysics, 62,* pp. 661-670

Klatzky, R.L. & Lederman, S.J. (1993). Toward a computational model of constraint-driven exploration and haptic object identification. *Perception-London*.

Klatzky, R.L., Lederman, S.J., & Metzger, V. (1985). Identifying Objects by Touch - an Expert System. *Perception & Psychophysics*, *37*(4), 299–302.

Klatzky, R.L., Lederman, S.J., & Reed, C. (1987). There's more to touch than meets the eye: The salience of object attributes for haptics with and without vision *Journal of Experimental Psychology: General*, *116*(4), 356–369.

Klatzky, R.L., & Lederman, S.J. (1995). Identifying objects from a haptic glance. *Percept Psychophys*, *57*(8), 1111–1123.

Klatzky, R.L., Loomis, J.M., Lederman, S.J., Wake, H., & Fujita, N. (1993). Haptic identification of objects and their depictions. *Perception & Psychophysics*, *54*, 170–170.

Lacey, S., & Campbell, C. (2006). Mental representation in visual/haptic crossmodal memory: evidence from interference effects. *Q J Exp Psychol (Colchester)*, *59*(2), 361–376. doi:10.1080/17470210500173232

Lacey, S., Campbell, C., & Sathian, K. (2007). Vision and touch: multiple or multisensory representations of objects *Perception*, *36*(10), 1513–1521. doi:10.1068/p5850

Lacey, S., Flueckiger, P., Stilla, R., Lava, M., & Sathian, K. (2010). Object familiarity modulates the relationship between visual object imagery and haptic shape perception. *NeuroImage*, *49*(3), 1977–1990. doi:10.1016/j.neuroimage.2009.10.081

Laird, D.A. (1932). How the consumer estimates quality by subconscious sensory impressions *Journal of Applied Psychology*, *16*(3), 241–246. American Psychological Association. doi:10.1037/h0074816

Lawson, R. (2009). A comparison of the effects of depth rotation on visual and haptic three-dimensional object recognition *Journal of Experimental Psychology: Human Perception and Performance*, *35*(4), 911–930. doi:10.1037/a0015025

Lawson, R., & Bulthoff, H.H. (2008). Using morphs of familiar objects to examine how shape discriminability influences view sensitivity. *Perception & Psychophysics*, *70*(5), 853–877. doi:10.3758/PP.70.5.853

Lederman, S.J., Klatzky, R.L., Abramowicz, A., Salsman, K., Kitada, R., & Hamilton, C. (2007). Haptic recognition of static and dynamic expressions of emotion in the live face. *Psychol Sci*, *18*(2), 158–164. doi:10.1111/j.1467-9280.2007.01866.x

Lederman, S.J., & Klatzky, R.L. (1987). Hand movements: a window into haptic object recognition *Cognitive Psychology*, *19*(3), 342–368.

Lederman, S.J., & Klatzky, R.L. (1996). Action for perception: Manual exploratory movements for haptically processing objects and their features. In A. Wing, P. Haggard, & R. Flanagan (Eds.), *Hand and Brain: Neurophysiology and Psychology of Hand* (pp. 431–446). San Diego: Academic.

Lederman, S.J., & Klatzky, R.L. (2004). Haptic identification of common objects: effects of constraining the manual exploration process. *Percept Psychophys*, *66*(4), 618–628. doi: 10.3758/BF03194906

Lederman, S.J., Loomis, J.M., & Williams, D.A. (1982). The role of vibration in the tactual perception of roughness. *Perception and Psychophysics, 32*(2), 109-116.

Lhote, M. & Streri, A. (1998). Haptic memory and handness in 2-month-old infants. *Laterality: Asymmetries of bidy, brain and cognition, 3*(2), 173-192.

Loomis, J. M., Klatzky, R.L., & Lederman, S.J. (1991). Similarity of tactual and visual picture recognition with limited field of view. *Perception*, *20*(2), 167–177.

Loomis, J.M., & Lederman, S.J. (1986). Tactual perception. In K. Boff, L. Kaufman, & J. Thomas (Eds.), *Handbook of perception and human performance*. New York: Organization.

Louw, S., Kappers, A.M.L., & Koenderink, J.J. (2002). Haptic discrimination of stimuli varying in amplitude and width *Experimental Brain Research*, *146*(1), 32–37. doi:10.1007/s00221-002-1148-z

Luo, Z., & Imamiya (2003). Color presentation mode affects human haptic memory for rough surfaces. Proceedings of the 2003 IEEE International Conference on Information Reuse and Integration, IRI - 2003, Las Vegas, USA.

Luo, Z., & Imamiya, A. (2004). Do colors affect our recognition memory for haptic rough surfaces In *Computational Science - Iccs 2004, Pt 3, Proceedings* (Vol. 3038, pp. 897–904). Presented at the Computational Science - Iccs 2004, Pt 3, Proceedings.

Newell, F.N., Ernst, M.O., Tjan, B., & Bülthoff, H. (2001). Viewpoint dependence in visual and haptic object recognition. *Psychological Science*, *12*(1), 37.

Norman, J.F., Norman, H.F., Clayton, A.M., Lianekhammy, J., & Zielke, G. (2004). The visual and haptic perception of natural object shape *Perception & Psychophysics*, *66*(2), 342–351.

Occelli, V., Spence, C., & Zampini, M. (2008). Audiotactile temporal order judgments in sighted and blind individuals. *Neuropsychologia*, *46*(11), 2845–2850. doi:10.1016/j.neuropsychologia.2008.05.023

Picard, D. (2006). Partial perceptual equivalence between vision and touch for texture information. *Acta Psychologica*, *121*(3), 227–248. doi:10.1016/j.actpsy.2005.06.001

Picard, D., Lebaz, S., Jouffrais, C., & Monnier, C. (2010). Haptic recognition of two-dimensional raised-line patterns by early-blind, late-blind, and blindfolded sighted adults *Perception*, *39*(2), 224–235. doi:10.1068/p6527

Plaisier, M.A., Tiest, W.M.B.B., & Kappers, A.M.L. (2008). Haptic pop-out in a hand sweep. *Acta Psychologica*, *128*(2), 368–377. doi:10.1016/j.actpsy.2008.03.011

Postma, A., Zuidhoek, S., Noordzij, M.L., & Kappers, A.M.L. (2007). Differences between early-blind, late-blind, and blindfolded-sighted people in haptic spatial-configuration learning and resulting memory traces. *Perception*, *36*(8), 1253–1265.

Pring, L., & Rusted, J. (1985). Pictures for the blind: An investigation of the influence of pictures on recall of text by blind children *British Journal of Developmental Psychology*. British Psychological Society.

Richardson, B.L., Wuillemin, D.B., & Mackintosh, G.J. (2011). Can passive touch be better than active touch? A comparison of active and passive tactile maze learning. *British Journal of Psychology*, *72*(3), 353–362. doi:10.1111/j.2044-8295.1981.tb02194.x

Röder, B., & Rösler, F. (2004). Compensatory plasticity as a consequence of sensory loss. In G. Calvert, C. Spence, & B. Stein (Eds.), *The Handbook of Multisensory Processes* (p. 915). Cambridge, MA: MIT Press.

Sadato, N., Ibaņez, V., Deiber, M., & Hallett, M. (2000). Gender difference in premotor activity during active tactile discrimination. *NeuroImage*, *11*(5), 532–540. doi:10.1006/nimg.2000.0566

Sanabria, D., Soto-Faraco, S., & Spence, C. (2005a). Spatiotemporal interactions between audition and touch depend on hand posture *Experimental Brain Research*, *165*(4), 505–514. doi:10.1007/s00221-005-2327-5

Sanabria, D., Soto-Faraco, S., & Spence, C. (2005b). Assessing the effect of visual and tactile distractors on the perception of auditory apparent motion. *Experimental Brain Research*, *166*(3-4), 548–558. doi:10.1007/s00221-005-2395-6

Sanders, A.F.J., & Kappers, A.M.L. (2008). Factors affecting the haptic filled-space illusion for dynamic touch. *Experimental Brain Research*, *192*(4), 717–722. doi:10.1007/s00221-008-1635-y

Sherrick, C.E. (1975). The art of tactile communication. *The American Psychologist*, *30*(3), 353–360.

Simões-Franklin, C., Whitaker, T.A., & Newell, F.N. (2011). Active and passive touch differentially activate somatosensory cortex in texture perception *Human Brain Mapping*, *32*(7), 1067–1080. doi:10.1002/hbm.21091

Spence, C., & Gallace, A. (2007). Recent developments in the study of tactile attention *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale*, *61*(3), 196–207. doi:10.1037/cjep2007021

Spence, C., & Ho, C. (2008). Multisensory warning signals for event perception and safe driving. *Theoretical Issues in Ergonomics Science*, *9*(6), 523–554. Taylor and Francis Ltd. doi:10.1080/14639220701816765

Stadtlander, L.M., Murdoch, L.D., & Heiser, S.M. (1998). Visual and Haptic influences on memory: age differences in recall. *Experimental Aging Research*, *24*(3), 257–272.

Stevens, J., Foulke, E., & Patterson, M. (1996). Tactile acuity, aging, and braille reading in long-term blindness. *Journal of experimental psychology: applied*, *2*(2), 91–106.

Stier, D.S., & Hall, J.A. (1984). Gender differences in touch: An empirical and theoretical review *Journal of Personality and Social Psychology*, *47*(2), 440. American Psychological Association. doi:10.1037/0022-3514.47.2.440

Streri, A., Lhote, M., & Dutilleul, S. (2000). Haptic perception in newborns. *Developmental Science*, *3*(3), 319–327. doi: 10.1111/1467-7687.00126

Tiest, W.M.B.B., & Kappers, A.M.L. (2007). Haptic and visual perception of roughness. *Acta Psychol (Amst)*, *124*(2), 177–189. doi:10.1016/j.actpsy.2006.03.002

Tiest, W.W.B.B., Norman, J., Kahrimanovic, M., & Kappers, A.M.L. (2010). Hand movements during haptic object exploration.*Perception, 39.* ECVP Abstract Supplement, page 132.

Titchener, E.B. (1909). *A text-book of psychology* (p. 558).

Trojan, J., Getzmann, S., Möller, J., Kleinböhl, D., & Hölzl, R. (2009). Tactile-auditory saltation: Spatiotemporal integration across sensory modalities. *Neuroscience Letters*, *460*(2), 156–160. doi:10.1016/j.neulet.2009.05.053

Turvey, M. (1996). Dynamic Touch. *American Psychologist*, *51* (11). pp. 1134-1152.

van der Horst, B.J., Willebrands, W.P., & Kappers, A.M.L. (2008). Transfer of the curvature aftereffect in dynamic touch. *Neuropsychologia*, *46*(12), 2966–2972. doi:10.1016/j.neuropsychologia.2008.06.003

Van Doorn, G.H., Richardson, B.L., Wuillemin, D.B., & Symmons, M.A. (2010). Visual and haptic influence on perception of stimulus size *Attention, Perception, & Psychophysics*, *72*(3), 813–822. doi:10.3758/APP.72.3.813

Verrillo, R.T. (1968). A duplex mechanism of mechanoreception. In D. Kenshalo (Ed.), *The skin senses.* Springfield: Thomas.

Verrillo, R.T., & Gescheider, G.A. (1975). Enhancement and sumation in the perception of two sucessive vibrotactile stimuli. *Perception & Psychophysics, 18*, 128 - 136.

Wagner, S.H., & Sakovits, L.J. (1986). A process analysis of infant visual and cross-modal recognition memory: Implications for an amodal code *Advances in Infancy Research*. Elsevier/JAI Press Inc.

Weber, E. (1996). *E. H. Weber on the Tactile Senses*. (H. Ross & D. Murray, Trans.). Erlbaum (UK): Taylor&Francis. (original works published in 1834 and 1905).

Whitaker, T. A., Simões-Franklin, C., & Newell, F.N. (2008). Vision and touch: independent or integrated systems for the perception of texture *Brain Res*, *1242*, 59–72. doi:10.1016/j.brainres.2008.05.037

Willis, F., & Hofmann, G. (1975). Development of tactile patterns in relation to age, sex, and race *Developmental Psychology*, *11*(6), 866.

Woods, A.T., Moore, A., & Newell, F.N. (2008). Canonical views in haptic object perception *Perception*, *37*(12), 1867–1878. doi:10.1068/p6038

Woods, A.T., O'Modhrain, S., & Newell, F.N. (2004). The effect of temporal delay and spatial differences on cross-modal object recognition. *Cogn Affect Behav Neurosci*, *4*(2), 260–269.

Zampini, M., Brown, T., Shore, D.I., Maravita, A., Röder, B., & Spence, C. (2005). Audiotactile temporal order judgments. *Acta Psychologica*, *118*(3), 277–291. doi:10.1016/j.actpsy.2004.10.017

Zimler, J., & Keenan, J.M. (1983). Imagery in the congenitally blind: how visual are visual images *J Exp Psychol Learn Mem Cogn*, *9*(2), 269–282.

Zuidhoek, S., Kappers, A.M.L., & Postma, A. (2007). Haptic orientation perception: sex differences and lateralization of functions. *Neuropsychologia*, *45*(2), 332–341. doi:10.1016/j.neuropsychologia.2006.05.032

Touch and memory:
A review on short-term and long-term memory registers[2]

ABSTRACT

This review presents a systematic review of studies on touch and memory. During this text we will explore designs and results of memory experiments with tactile stimuli, highlighting the relevance of the study of tactual stimuli and memory. We will structure this text attending to the definition of memory registers: first we will focus on immediate sensory memory studies, then short-term memory studies and working memory studies, and finally, long-term memory studies. This text includes a reflexive analysis of the impact of the experimental designs, stimuli, participants, and type of stimuli exploration, on the results. We will end this review by presenting future paths for research on touch and memory, as a consequence of the analysed studies.

Since the works of the Greek philosophers, memory has been a central topic in the literature about human cognition. In the beginnings of psychological research, Ebbinghaus (1885/1913) presented the initial systematic works on human memory and until today, much experimental work was conducted on this theme.

With the development of cognitive approaches to memory (see Broadbent, 1958, and Neisser, 1967) authors started to conceptualise memory, not as a unitary system, or a simple sequence of associations, but as a system composed by more than one structure (Tulving & Craik, 2000). In the 1960s the consensual view of memory was translated by a scheme that presented four central components: cues from the environment, sensory memory, short-term memory, and long-term memory (Baddeley, Eysenck, & Anderson, 2009).

Atkinson and Shiffrin's (1968) modal model can be taken as an example of that structural perspective on memory. This model assumed the existence of a sensory register, specific to the sensory modality that perceived the stimuli (visual, auditory, haptic) and a short-term memory store that the authors called the *temporary working memory*. This store determined response outputs and executed control processes like rehearsal, coding, decision and retrieval strategies, that would allow the transition of information to a long-term memory store that had a permanent register (Atkinson & Shiffrin, 1968). However, neuropsychological evidence showed that a unitary short-term memory system was not as crucial to learning and reasoning has described in the model, since patients with short-term memory deficits revealed normal long-term memory (Shallice & Warrington, 1970). Also, Atkinson and Shiffrin's (1968) hypothesis that learning was dependent on the time information was held in short-term memory, was not confirmed (e.g., Tulving, 1966).

Following these drawbacks of the modal model, the levels of processing model is suggested by Craik and Lockhart (1972). This model offered a more general theoretical framework for memory research, and was

---

[2] Paper *in preparation*

focused on memory processes in detriment of memory stores. A basic assumption of the model was that what determined the retention of information in long term memory was the type of processing the stimuli were subject to, in such a way that deep processing levels would originate better encoding and long-term retention. In this model, the authors assume the existence of a *primary memory store* that is relevant to how stimuli are processed, but the model is mainly focused on encoding effects on long-term memory.

At this point, and alternative structural model is presented by Baddeley and Hitch (1974). The *working memory model* is an unavoidable and central model in today's memory research. Working memory was presented as a complex dynamic system, composed by a main component, the *central executive*, and two subcomponents, the *phonological loop* and the *visuospatial sketchpad*. The central executive is presented as a reasoning, attention and decision component, while the phonological loop is responsible for encoding of verbal and auditory stimulation and the visuospatial sketchpad is associated with the processing of visual and spatial information (Baddeley & Hitch, 1974). This model was confirmed by a series of studies on visual and auditory modalities and its specificity has grown since 1974, and nowadays the visuospatial sketchpad is theoretically presented as a dual system, with specific visual and spatial components, and the phonological loop is also thought to be separable in an articulatory and a phonological system. Moreover, in 2000, Baddeley added a new subcomponent to the model, the *episodic buffer,* which is responsible for binding information from the other two subcomponents and from long-term memory. This subcomponent was presented in the sequence of a series of experimental works that showed that the phonological loop and the visuospatial sketchpad communicated directly with each other, providing integrated information. Recently, as a result of the large number of studies on binding and the episodic buffer role on working memory, the function of the episodic buffer was redefined (Baddeley, Allen, & Hitch, 2010), and this subcomponent is now presented as a passive storage that maintains information previously bound in the other two subcomponents. Within this model, memory is presented as *amodal* or as sensory modality independent, since regardless of the encoding modality, information must be manipulated in working memory through a verbal (or auditory) code or a visuospatial code.

Although the concept of working memory appears in Baddeley and Hitch's (1974) model as an elaboration on the notion of short-term memory, the two concepts still coexist. Establishing a clear theoretical distinction between the two seems to be complicated (Baddeley et al., 2009) but the distinction is most likely associated with the type of memory task that is designed to measure each one of them (Unsworth & Engle, 2007). Nowadays, the term working memory usually refers to the concept as described by Baddeley and Hitch (1974), while short-term memory corresponds to the designation of a temporally determined store for straightforward information. As such, tasks that do not involve the central executive (e.g., digit span) are measures of short term memory, while tasks that require stimuli manipulation (e.g., inverse digit span) are working memory evaluation tasks (Unsworth & Engle, 2007). In the present review we present short-term and working memory research reports separately, attending to the previous classification, according to the type of tactile or haptic task that is solicited from the participants - simple tasks will be analysed under the short-term memory topic, while complex tasks will be reviewed under the working memory heading.

The number of studies on working memory and long term memory in touch is very scarce, although there is a fair amount of studies addressing short-term memory for tactile stimulation. Of particular interest for the present work are the papers published by Millar (1999) and Gallace and Spence (2008; 2009). Millar's (1999) work is a critical review of short-term memory models from the perspective of data collected in tactile memory experiments. The author suggests that memory models should attend to modality specific encoding of inputs, connections between the stored and retrieved information, the rehearsal systems present at encoding, and the relevance of familiarity of the tasks (both procedures and encoding strategies). Gallace and Spence (2008) present an interesting review on the processes of tactile consciousness and awareness. These authors review literature on numerosity judgments, namely spatial numerosity and subitizing in touch; processes of change blindness and inattencional blindness; short-term memory in touch; phantom limb sensations and other tactile illusions; and finally present reviews on neuropsychological and psychophysiological studies on tactile consciousness. Overall, this review enlightens some tactile specificities in cognition and analyses tactile performance in crossmodal and multisensory conditions. The review on tactile memory, published in 2009 (Gallace & Spence, 2009) has a central focus on tactile memory in multisensory contexts, and in the comparison of tactile and visual memory systems. The authors analyse previous literature on haptic recognition of objects and faces, on blind participants' memory, and on the development of tactile memory, presenting a final approach to the neural correlates of tactile memory.

The present review constitutes a deepening of the earlier reviews on tactile memory, focusing on the topic of memory and analysing haptic and tactile memory results in relation to memory models, not only for immediate and short-term memory paradigms, but also for the unexplored topics of tactile and haptic working memory and long-term memory. In the next pages we will analyse the results of various studies published on tactile and haptic memory. This review is organised attending to the type of memory that is tested: immediate sensory memory, measured through partial report paradigms, short-term and working memory, measured by serial recall tasks and interference tasks, and long term memory, measured in recognition and recall paradigms. In each part of the work we will consider the implications and future directions of research on tactile and haptic memory.

1. IMMEDIATE SENSORY MEMORY IN TOUCH

The question of how many items one can retain in brief stimuli presentations was first address by Sperling (1960). In this work, Sperling (1960) compared participant's performance in recalling items presented in a consonant matrix manipulating: a) the number and disposition of consonants in the matrix; b) the time interval from presentation to recall; c) the exposure duration, and d) the report procedure. Results showed that after a brief visual presentation of a consonants matrix, participants were able to recall an average of four or five stimuli regardless of the size of the matrix in whole report conditions (participants were asked to recall all the elements of the matrix and instructed to guess when they were not sure about them). However, in partial report conditions, in which a sound probe targeted the row in the matrix that should be recalled, participants presented few errors, regardless of the row they were asked to recall. This result made it possible to estimate the total number of items that could be recalled immediately after the visual presentation, and this estimation pointed to 12 to 18 items, a result that revealed an immediate sensory memory of high capacity, but also very brief duration. These results later originated the term *iconic memory* (Neisser, 1967) to describe a very brief visual sensory register that presents a very rapid decay (see Coltheart, 1980, for a review).

A similar auditory store was later presented (e.g., Cowan, 1984) as *echoic memory*. Empirical studies revealed that echoic memory although being a brief auditory store, presented much longer durations than the iconic store (e.g., Darwin, Turvey, & Crowder, 1972; Watkins & Watkins, 1980): while there are intervals in the order of milliseconds for immediate visual memory, time intervals in the immediate auditory store correspond to seconds. Also, attending to the number of items advantage in whole report when compared with partial report, the auditory advantage, around four items more in the estimated partial report condition (Darwin et al., 1972) is much less than the visual advantage of around 12-18 items in partial report (Sperling, 1960).

One of the first systematic studies of immediate sensory memory in touch was conducted by Bliss et al. (1966). Inspired by the works of Sperling (1960) in visual sensory memory, Bliss designed a complex procedure to evaluate immediate memory in touch. The adaptation of the partial report paradigm for touch, conducted by Bliss et al. (1966), implied the use of airjet stimulators in both hands, in three locations in every finger, except the thumb. Participants were asked to recall the positions through a code of numbers and letters that represented, respectively, the fingers and the positions where the airjets were applied. This study revealed that a very short-term memory for touch existed, equivalent to iconic memory. However, the capacity of the tactile immediate storage seemed to be smaller than its visual counterpart. A relevant aspect to consider about these data is the complex recall system that was presented to the participants in Bliss et al. (1966) study. Participants did not only had to recall the location of the stimuli, but also recall the number that represented each finger and the letter that represented each location within the finger. Such a procedure implies a strong verbal encoding of tactile information, and might have been measuring more complex processes than just tactile immediate memory (Gallace & Spence, 2008). Another critical feature of this study (Bliss et al., 1966) is the fact that what was being recalled was stimuli location and not the stimuli themselves. This aspect is crucial because it can be argued that the experiment was testing memory for location and not actually tactile memory in the sense that no tactile features from the stimuli needed to be retained or retrieved. Moreover, studies within the auditory modality have shown that immediate memory when location is required seems to be worst than immediate memory when only stimuli recall is requested (Darwin et al., 1972).

More recently, Gallace, Tan, Haggard, and Spence (2008) have presented a study that evaluated the presentation of vibration stimuli throughout the body, and not only on the hands. The authors argue that while memory for location in the hand can easily be tagged using the name of the fingers, when vibrations are presented in the whole body, it is not easy to attribute them specific verbal tags. In this study the authors evaluated the report of stimuli presented across the body surface according to numerosity judgements and partial report procedures. Parallel presentation of up to six different stimuli in one of seven different locations (distributed in arms, legs and waistline) was applied. Results show that in the numerosity judgement condition participants were able to recall up to three stimuli, while in partial report conditions (participants had to report if a stimulus was presented in a cued location) performance was up to five positions. Results also revealed a tradeoff effect between the number of stimuli presented and the duration of the representation: as the number of stimuli was increased, the decay function was faster.

The previous studies confirm the existence of an immediate tactile sensory store, that can be evaluated using a procedure equivalent to the one that led to the concepts of iconic and echoic memory. However, the tactile advantage in partial report is a lot smaller than the visual advantage and might be considered similar to the auditory store. Processing in both tactile and auditory modalities is sequential and not parallel as in vision, which might be affecting the capacity of tactile and auditory stimuli to retain information presented in parallel. Another possible explanation for the smaller effect of partial report in touch might be related to the nature of the presented stimuli. While in visual and auditory procedures the most frequent stimuli are numbers and letters which are highly familiar stimuli, in tactile experiments the stimuli used were airjets and vibrations, both rare and abstract stimuli which might have affected performance.

Evaluating tactile or haptic performance in very short time periods is complicated and demands precise equipment. However, the timings of tactile immediate memory might themselves be different from intervals in other modalities. Like previously mentioned, echoic memory seems to have a larger duration than iconic memory and an equivalent tactile storage probably presents its own idiosyncrasies. The time necessary to perceive and process a tactile complex stimuli is, as was demonstrated earlier in this work, longer than the time needed in visual perception and this property can probably affect all memory registers.

2. SHORT-TERM MEMORY IN TOUCH

In 1969 Gilson and Baddeley published a study on tactile short-term memory. In this experiment the authors asked participants to recall a tactile stimuli (touch with a pen) applied to the forearm after different delays that varied from immediate recall to a 60 seconds interval. Recall was performed by pointing to the touched location. The task was performed in single task condition, in which participants just had to remember the tactile stimuli, and in dual task condition, in which participants had to count backwards in threes. The dual task condition intended to impair any kind of verbal rehearsal during the tactile stimuli presentation. Results show that in dual task conditions, during the first 15 seconds there seemed to be no effect of interference, but from 15 seconds on participants showed a growing number of errors and after 45 seconds delay participants were not able to accurately recall the stimuli. In single task conditions there was a decline in accuracy in the first 10 seconds, followed by an increase in accuracy in the following five seconds, and from that time on there was a slow decay function. Considering these results the authors infer that tactile short term memory is dependent on two distinct processes: a sensory trace, responsible for the first 10 seconds function, and a more durable process, not affected by verbal interference but influenced by some type of rehearsal.

Later, Miles and Borthwick (1996) use a similar procedure to analyse tactile short term memory, comparing the effects of articulatory suppression (repeating the word “the”), counting backwards in threes, and tactile interference (moving a ball-point pen back and forth over the tactile locations in the delay interval). Results revealed that recall decays as the interval between presentation and recall increases in any of the conditions. The data do not support Gilson and Baddeley’s (1969) hypothesis of a dual process in tactile short-term memory, revealing a straightforward decay function. Also, data showed that articulatory suppression and counting backwards had the same effect on tactile short term memory, and that tactile interference impaired recall as much as articulatory suppression and as much as both presented simultaneously. These data do not suggest that verbal interference is affecting location memory, as assumed by Gilson and Baddeley (1969), since there are no differences in tactile and verbal interference types and the two types of interference presented simultaneously do not result in worst performance than when presented separately. The authors suggest that both interference types affected separate processes in tactile short term memory, with tactile interference impairing stimuli discriminability and verbal interference implying the use of central resources that would otherwise be allocated to the memory task.

The previous study (Miles & Borthwick, 1996) results are in accordance with another study on tactile short-term memory presented by Sullivan and Turvey (1972) in which participants had to report the location where a discrete tactile stimuli was presented in the arm whether in single (tactile task only) or dual task (simple arithmetic operation during the retention interval) conditions. Results showed that a simple decay function was found for tactile stimuli in both conditions, with the single task conditions presenting better performance than dual task condition. The authors assumed that these different results depended more on the participant’s strategies to perform the task, rather than on rehearsal prevention. As such, in this study short-term tactile memory presented a typical decay curve, dependent on the duration of the retention interval. Later, the same authors present a study with a new procedure presenting tactile stimuli in three of four possible locations in the fingers of the left hand. Results revealed that forgetting reached a maximum within six seconds, and that both verbal and nonverbal distractor tasks affected performance. The authors suggest an overlap of visual and tactile processing systems for this task (Sullivan & Turvey, 1974).

One important aspect in the previous studies is that participants were asked to recall the location of the tactile stimuli and not the tactile stimuli themselves, which implies the use of spatial and possibly verbal codes to successfully recall the items. Another relevant aspect regards performance considering the duration of the retention intervals. These previously presented data suggest that an immediate sensory memory for touch could last for 10 seconds (see Gilson & Baddeley, 1969) and short-term memory could present a duration of about 45 seconds, and these data correspond to memory for tactile location and not simple tactile stimulation (retrieval of a tactile feature).

Tactile short term memory was also explored attending to the two-point threshold by Murray, Ward and Hockley (1975). The two-point threshold is a technique for measuring spacial acuity in touch and consists in the presentation of stimulation in two points simultaneously, shortening the distance between the two points during the experiment with the objective of determining the minimum distance between the points that can be perceived by the participant (Sherrick & Craig, 1982). The analysis of tactile short-term memory revealed that the most sensitive areas of the skin, where the threshold was smaller, were also the areas where the least degree of forgetting was detected.

Another group of studies has concentrated on the tactile suffix effect. The suffix effect was originally tested with verbal stimuli and consisted in the presentation of a suffix (an extra item) immediately after the to be remembered list of words, numbers or digits. In control conditions (no suffix) auditory presentation of the words showed a strong recency effect (last words on the list were better recalled than words in the middle of the list), while in visual presentation the recency effect only exist for the last item. However, in suffix conditions, the pattern of responses for auditory stimuli becomes identical to the pattern in visual conditions (e.g., Conrad & Hull, 1968). Watkins and Watkins (1974) explore the existence of a tactile suffix effect, assuming that the presence of such an effect would prove the maintenance of purely tactile information in short term memory. They apply tactile passive stimulation (touch with a ball-point pen) to the participants fingers of both hands (except thumbs) and ask them to recall the order of presentation, training them to associate each finger with a number from one to eight. Their results confirm the existence of a tactile suffix effect, with recall in control conditions showing a recency effect that disappears after a tactile suffix. Another study on the tactile suffix effect compares performance in visual and tactile modalities for the presentation of letters and non-verbal stimuli, and confirms the existence of a tactile as well as a visual suffix effect (Manning, 1980).

Using more complex stimuli, Susanna Millar developed a series of studies on tactile memory in the 1970s with children, and across different tasks. In one of these experiments it was shown that verbal and visual distractors did not affect tactile recognition of shapes in intervals as long as nine seconds and results suggested differences in recognition of visual and haptic targets (Millar, 1972). A later study comparing blind and sighted children's recognition of nonsense shapes (Millar, 1974) revealed that either a verbal distractor (counting backwards in threes) or a movement distractor (organise a set of barrels according to size) during the retention interval affected the children's ability to recognise the touched shape. Blind children were faster, but committed more errors in recognition, and as such no advantage was found for blind or sighted children in this task.

Other studies have also confirmed the robustness of tactile short-term memory, with three-dimensional objects. Bowers, Mollenhauer and Luxford (1990) evaluated the participants' capacity to recall texture, shape, and time durations of the presentation of haptic stimuli and showed that haptic recall of tactile properties was excellent (between 95 and 99%) throughout testing, although time estimation was considerably poor (60% correct answers). Kiphart and collaborators (Kiphart, Auday, & Cross, 1988; Kiphart, Hughes, Simmons, & Cross, 1992) also presented two studies on tactile short-term memory with three-dimensional objects. In the first study (Kiphart et al., 1988) they showed a high haptic performance and no evidence of a decay function in intervals up to 80 seconds, either in rest intervals, or with intervals filled with activities (counting, squeezing objects or tapping). The authors argued that this result might be a consequence of a highly effective haptic system, since the presented objects were not easily verbally “labeled” and had identical texture, not allowing for texture discriminations (and as such controlling the possibility of verbal tags of the stimuli either by naming or by texture identification). In a second study (Kiphart et al., 1992) the authors attempted to further explore tactile memory for complex objects, using a more homogenous set of stimuli, shortening the exploration times, and increasing the number of tested delay intervals. Results revealed a decay function according to interval delay only between 15 seconds and 30 seconds intervals, and still showed a good performance from the subjects in the high score group.

As illustrated in this topic, tactile and haptic short-term memory data point to a tactile specificity in memory, although there are some unclear results, specially in multisensory and crossmodal research paradigms. To us, this apparent incongruence can be justified by the implicit demands of the presented tasks. In both tactile and visual modalities spatial cues are relevant and needed to encode stimuli. Within research paradigms that enhance the relevance of spatial encoding (like asking participants to recall a stimuli location) or to recover stimuli properties that can be processed simultaneously through vision and touch (for instance attending to shape or size of an object) it is expected that visual and tactile or haptic conditions present shared processing, and that vision, as a result of its parallel processing shows faster and even better recognition and recall.

3. WORKING MEMORY IN TOUCH

Baddeley and Hitch’s (1974; Baddeley, 2000) working memory model has been one of the most influential models in memory research since its presentation. Research on haptics is no exception to this rule, and as such studies exploring working memory and touch have been designed in an attempt to test how information acquired by touch was processed in memory.

Within a working memory framework, spatial, visual, and verbal encoding and processing are crucial. In this section we will explore the relation between haptics and spatial, visual, and verbal encoding, attempting to understand if these alternative forms of encoding haptic information are sufficient to explain the results obtained with haptic stimuli. We will conduct a critical review of each of the presented studies to highlight the relevance of experimental manipulation in haptic memory evaluation.

One of the most frequent paradigms in the evaluation of working memory is the interference procedure, or dual-task procedure. This paradigm states that if two tasks share the same cognitive resources, performing both tasks will lead to worst performance than performing each task separately (e.g., Oberauer & Göthe, 2006). Tactile and haptic working memory research is not an exception, and the interference paradigm was used by some authors to access the nature of memory in touch.

Using the dual task paradigm, a crossmodal visuo-haptic study comparing young adults, older adults, and mild cognitive impairment older adults showed that working memory spans for haptic tasks were smaller than for visual tasks in all of the groups, however, this result could be a consequence of presenting items simultaneously in the visual task, and sequentially in the haptic task, which required a much longer presentation time (Paz, Mayas, & Ballesteros 2007). The authors used an adapted Corsi blocks haptic task, in which the participant had to study each position sequentially (only one block presented in the matrix at one time) and at the end, remember all the locations, placing a block sequentially in all the presented locations. For the visual task, participants saw a matrix on the screen with half the squares white and half black. In both haptic and visual conditions, participants had to reproduce the matrix after a retention interval. The retention interval was filled by a haptic task (rolling a block counter-clockwise) or by a visual task (identify if two arrows were pointing to the same place). The haptic Corsi blocks task clearly presented an increased difficulty since participants were forced to encoded each item in the matrix individually, while in the visual condition, by presenting the whole matrix simultaneously, the participants could recall the items according to general patterns. Moreover, time is a crucial variable in span tasks, and the haptic task takes successively more time than the visual task (participants had five seconds to explore the visual task, independently of the number of items, and had five seconds to explore *each* item in the haptic task).

Another study exploring haptic working memory with interference tasks was presented by Sebastián, Mayas, Manso, and Ballesteros (2008), and consisted in the presentation of visual or haptic 3x3 matrices (two targets and one distractor in each trial). Participants had to remember the position of the targets and ignore the distractor after a six seconds retention interval that was filled with either a haptic task (explore an empty matrix with the other hand), a visual task (following a continuous dot on the screen), a verbal task (articulatory suppression), or a visual static control task (look at a fixation cross). Only spatial interference, either haptic or visual, affected performance, and the effect was more visible when the interference task was of the same modality as the main task (haptic interference in haptic task and visual interference in visual task), and the haptic task was more strongly affected by interference than the visual task. In this strongly spatial task (remembering positions in a matrix), verbal interference showed no effects, as would be expected from Baddeley and Hitch's (1974) working memory model. Moreover, visuospatial interference (following a dot on the screen) did not impair haptic recall more than the control task (staring at a fixation cross). Likewise, haptic-spatial interference (exploring an empty matrix) did not impair performance in the visual task. These results can indicate that there is a modality specificity that overwrites common spatial encoding. However, we must be cautious in the interpretation, since the interference tasks were very different, and might even imply different resources. In addition, the spatial nature of the interference tasks can be questioned: is following a dot over the screen sufficient to elicit spatial encoding, or is it a more automatic task? Moreover for the haptic task, participants might have been inattentive to the haptic exploration of the empty matrix. There is a clear need to control for the nature of the interference tasks; the participants' involvement in the task, as well as to control for task difficulty. Only then we can draw conclusions on the effects of spatial interference. In this study, the results might just be reflecting an increased complexity of the task by preventing rehearsal of the stimuli in the target modality, and not specifically spatial encoding.

It has been shown previously in this review that a rather robust group of studies has confirmed the relevance of spatial processing in touch, and has suggested that spatial processing shares the same operations and structures in vision and touch. Research on memory for touch has also focused on the role of visuospatial sketchpad on haptic encoding. For instance, Giudice, Betty and Loomis (2011) showed that the number of errors and latency patterns when learning visual and haptic maps was very similar, and this result was applicable to blind participants as well, assuring that this pattern similarity was not due only to a visual encoding of the haptic information. A study on spatial neglect (Schindler, Clavagnier, Karnath, Derex, & Perenin, 2006), a neurological condition that prevents patients from being aware of stimuli on the side contralateral to the lesion, concluded that the same general process determined the biases in both modalities. A functional magnetic resonance imaging study (Ricciardi et al., 2006) also argued in favour of shared spatial working memory representations in visual and tactile modalities after verifying that similar fronto-parietal networks were activated in a tasks with two and three-dimensional matrices presented visually or tactually. However, studies attending directly to the relation between touch and vision have frequently reported separate processes (e.g., Easton, Greene, & Srinivas, 1997; Whitaker, Simões-Franklin, & Newell, 2008). We will analyse a group of working memory studies on touch evaluating designs and procedures and attempting to understand how tactile and haptic systems are processed.

Besides the approaches centered on the impact of the visuspatial aketchpad on haptic memory, some researchers have tried to explore the role of verbal representations, and consequently the contribute of the phonological loop to haptic memory. For instance, Lacey and Campbell (2006), using a crossmodal paradigm, explore crossmodal representations between vision and touch in the recognition of familiar and unfamiliar objects. The interference experiments required participants to touch or see a series of objects and perform a haptic task (moving an object with the one hand), visual task (look at a screen presenting dynamic visual noise), or a verbal task (hear a non-relevant text through headphones), either at encoding or retrieval. The authors only present haptic-visual and visual-haptic conditions, and no intramodal conditions in the study. Results reveal that familiar objects are not affected by any type of interference at encoding, while unfamiliar objects' recognition is affected by verbal and visual interference. None is impaired by haptic interference (Lacey & Campbell, 2006). Interference at retrieval led to a less clear pattern of results, revealing no main effect of interference. However, unfamiliar objects' visual recognition is affected by visual interference, and haptic recognition is affected by verbal interference. Haptic interference did not impair recognition in either condition. The authors argue that the familiar objects representations might be very robust and could not be disturbed by interference, whilst unfamiliar object representations might recur to both object description (verbal) and mental imagery (visual). A question that rises from this study is the equivalence of the interference tasks. With tasks that do not require an answer from the participants we are not able to assure that the same amount of cognitive resources is being activated by each one of them. Also, considering the hypothesis that familiar objects representations are robust, we can suppose that the results might have been different with more demanding interference tasks. Considering the low number of items in each studied list, and the very high level of performance in recognition in every condition (about 15 items in a list of 16 for familiar objects and about 13 items for unfamiliar ones), we can suppose that these task was not sufficiently demanding to reveal any type of disadvantage, and within a working memory perspective, it would be crucial to present truly demanding tasks in interference conditions to be able to depict some conclusions on haptic working memory.

A recent study, within the interference paradigm, reported that haptic perception of raised line drawings was impaired by both verbal (articulatory suppression) and visual (dynamic visual noise) interference at exploration, and the authors suggest that haptic information is re-coded into verbal and visuospatial codes (Holtby & D'Angiulli, 2011). However people's ability to recognise raised line drawings is not very good (Wijntjes, van Lienen, Verstijnen, & Kappers, 2008) and these type of stimuli, also known as haptic pictures, have a strong visual component, depriving people from essential haptic cues such as texture, temperature, and relief. Moreover the exploratory procedure was not a free manipulation task, but a guided exploration, in which the experimenter guided the participants' finger through the raised line drawings at a constant pace. Considering that the stimuli can be associated with the visual modality, since they represent a tactile form of a visual representation (picture), and were common stimuli (e.g., fruits), they could have easily generated a verbal representation. All of these variables might have led to a poorer haptic performance and one can argue that truly haptical cues were not available at exploration and might not have been processed since they did not facilitate the task. The stimuli's texture, temperature, and relief was identical, and as such it could have been more helpful for the participants to try to remember the objects by their name or by a mental image of the haptic picture.

In a study comparing blind and sighted participants performance in an *n-back* task with letters presented tactually or visually and Bräille letter presented tactually, Bliss, Kujala, and Hämäläinen (2004) report that performance decreases according to memory load in every condition, that sighted participants perform worst in the tactile raised letters task than blind participants, and that sighted participants visual task performance is better than blind participants raised letters performance but equivalent to blind participants' Bräille letters performance. The authors conclude that the blind participant's tactile working memory capacity is similar to sighted participants' visual working memory capacity. In a second study only with sighted participants and the same task, the authors compare high and low performance participants in visual and tactile conditions and conclude that the tactile task generates more variability and is less accurate than the visual one (Bliss & Hämäläinen, 2005). It is worth noting that tactile presentation of letters cannot be directly comparable to visual presentation: the presentation times were identical in both modalities, which means that participants in the visual condition had more time than needed to perceive the stimuli, while participants in the tactile condition had to use that time to explore the letter. Another significant aspect, is that letters are verbal stimuli that do not need to be encoded through visual or tactile codes. Participants could just be rehearsing the items verbally and the differences is performance can result of a simple task difficulty effect, in which tactile stimuli took longer to be identified, and as such were rehearsed for shorter times.

From a theoretical point of view, memory and touch have been addressed by Millar (e.g. Millar, 1999), Kaas (e.g. Kaas, Stoeckel, & Goebel, 2008), and Cohen (e.g. Cohen, Scherzer, Viau, Voss, & Lepore, 2011).

In a review on memory for touch, Millar (1999) presents results on a series of experiments with blind and sighted children, empathising the role of movement for tactile perception and memory. Millar argues that there is tactile specificity in human memory, and highlights studies on memory that reveal differences between verbal and tactile stimuli (e.g. Millar, 1975), and also between visual and tactile stimuli (e.g. Millar, 1972). According to the author, there is a form of tactile rehearsal that can be attributed to a structure like a *movement loop* that would be responsible for the repetition of haptic movements, contributing to the maintenance of tactile information in memory.

Kaas et al. (2008) suggest the integration of a tactual buffer in the Baddeley and Hitch's (1974) working memory model, in which haptic features like temperature or texture could be bound together, forming integrated representations of the touched stimuli.

Recently, a new theoretical perspective on tactile working memory has been presented (Cohen et al., 2011). Following the integration of findings from research with blind participants, the authors argue that working memory is a dynamic system, neurologically flexible, and dependent on experience.

Cohen et al. (2011) model hypothesises an experience-based multisensory model, where working memory specificity exists initially to all types of sensory modalities, but is modulated by experience and becomes expert in the most frequent modalities, usually vision and audition in most people, but can be specialised in other modalities as well, as is the case of tactile memory for blind participants.

In a study evaluating tactile working memory for Bräille characters (Cohen, Voss, Lepore, & Scherzer, 2010) with completely blind, blind with residual vision and sighted participants, the authors found that completely blind participants' working memory for Bräille letters under articulatory suppression was as good as sighted participants' visual working memory for letters. Also, the completely blind participants presented a better working memory than participants with residual vision in the working memory Bräille task. In a second experience, participants had to perform the Bräille working memory task in two interference conditions: performing a mental arithmetic task or a mental block displacement task. Completely blind participants performance in the Bräille task was similar to the performance of the two other groups in the visual letter task. The authors conclude that working memory can be modulated by experience. In the completely blind, the visuospatial sketchpad is not fully developed, since the participants do not have visual experiences, and its resources are mobilised to tactile memory, a central information path in the blind. Likewise, Burton, Sinclair, and Dixit (2010), in a study evaluating working memory for vibrotactile frequencies in blind and sighted participants, report that the involvement of the occipital cortex in the task suggests a sensory contribution in tactile processing in the blind that is parallel to the sensory contribution of vision in sighted participants.

This new perspective on working memory (Cohen et al., 2011) does not seem to make sense within the working memory model suggested by Baddeley and Hitch (1974), as it suggests a different structure of the working memory system, that involves what might be understood as a general subcomponent, that entails sensory-modality specificity, and that can be adjusted according to the system's needs and to the frequency of inputs, always interacting with long-term memory representations. This approach would comprise the understanding of data from all sensory modalities, and would allow the integration of information between modalities and with long-term representations. Further research with sensory deprived participants would be interesting to clarify and possibly generalise the model to other populations besides blind participants and tactile memory. The model just as presented does not allow predictions or tests about the nature of haptic memory in sighted participants, although it can explain the differences on tactile performance with natural and abstract stimuli focusing on familiarity and previous experience with that type of stimuli.

Previous research on working memory for touch has been conducted with stimuli that could be visually of verbally encoded and rehearsed, not allowing an effective test of memory in conditions where tactile features are the central cues to retain. Also, most previous studies have not adapted working memory paradigms to the specificity of tactual presentation, not using real objects or not allowing for free exploration of the stimuli.

From the previous review of working memory in touch, four main conclusions emerge: 1) there are few studies directly exploring working memory in touch; 2) previous studies have not explored haptic memory in optimal conditions such as free exploration of complex objects); 3) the interference paradigm is a valuable procedure that needs to be further explored within haptic working memory research, presenting truly demanding tasks to evaluate performance in high load conditions; and 4) although previous research apparently presents confounding evidence, once we analyse the particularities of the procedures, haptic specificity in working memory seems to be a reliable hypothesis.

4. LONG-TERM MEMORY IN TOUCH

Although the relevance of long-term memory representations for haptic perception has been noticed by several authors, studies on this topic are rare. To our knowledge, only Nabeta and Kusumi (2007) have directly approached this theme in an unpublished study.

The study of long-term memory has been focused on memory for visual stimuli or for words and sentences, and what we can learn from these experiments is that long-term memory seems to present a virtually unlimited capacity. Brady, Konkle, Alvarez, and Oliva (2008) have demonstrated, through an n-back procedure, with 2500 object pictures presented for five and a half hours, that participants are able to correctly differentiate presented from non-presented images with intervals as long as 1023 items (1024-back task).

However, long-term memory on touch is still unexplored and there is no memory capacity estimation, although previous studies on haptic perception seem to suggest that haptic long term memory should be large as well (Bushnell & Baxt, 1990; Klatzky, Lederman, & Metzler, 1985).

In a rare study on long term haptic memory (Nabeta & Kusumi, 2007) compared memory performance between touch and vision in recognition of lists of everyday objects with extensions of 100 or 500 items. Results revealed that haptic memory was superior to visual memory in both list extension conditions, but performance in both vision and touch was very high regardless of list extension, indicating that the number of items that could be recognised is probably larger than 500.

Pensky, Johnson, Haag, and Homa (2008) in a crossmodal visuo-haptic study with intramodal conditions, showed that haptic memory resisted for a week, whether it was tested in the same modality or in a different one. Participants in this study were allowed to manipulate 40 everyday objects for 15 seconds each and were informed that a memory test would be presented at the end. Considering that the foils in the recognition tasks were other exemplars of the presented objects (e.g. for the item *ball* the target item could be a football and the foil a volleyball), participants must have been retaining specific haptic cues about the objects, and not only their names. These data reveal that some type of haptic code is stored in long-term memory, allowing for the differentiation of specific tactile cues between target and foil items, since neither a visual representation generated through touch, nor a name-tag would have allowed the distinction between two exemplars of the same object.

In spite of the lack of experimental work in long-term memory for touch, we are led to believe that a long-term register for haptic memory exists allowing both the recollection of a stimulus or episode through touch (for instance, recalling a past event when the rain touches your face), and intentionally recollecting the tactile feeling in the absence of the tactile stimuli (being able to recall the sensation of your bed linen). Likewise, we know that haptic sensations can elicit emotions (e.g., McGlone, Vallbo, Olausson, Loken, & Wessberg, 2007), which might imply a sensory-specific print in our episodic and emotional memories.

5. CONCLUSIONS

Touch and memory have been studied mainly in short-term memory registers with abstract stimuli and in passive touch conditions. As mentioned previously, these conditions are not optimal for tactual performance (Fernandes & Albuquerque, submitted) and as such might be providing results that do not correspond to real measures of memory for touched items. It is important evaluate tactual memory in conditions similar to the ones in which we experience objects in everyday life.

Some researchers have developed paradigms adjusted to the specificity of touch processing, allowing longer exploration times, presenting everyday objects and allowing active exploration, and these experiments resulted in high levels of performance for touch (e.g. Nabeta & Kusumi, 2007; Pensky et al., 2008), contrary to the low levels of performance found with abstract stimuli (e.g. Gilson & Baddeley, 1969).

Results of studies on haptic memory appear to imply a haptic specificity in memory, indicating that participants are able to encode, process, maintain and retrieve tactual information, without loosing its perceptual characteristics, and suggesting that stimuli perceived by touch do not need to be encoded through visual or verbal codes. This hypothesis of haptic specificity in memory needs to be further explored, clarifying the processes and memory storages responsible for the cognitive manipulation of haptic information.

REFERENCES

Atkinson, R., & Shiffrin, R. (1968). Human memory: A proposed system and its control processes. In K. Spence (Ed.), *The psychology of learning and motivation: advances in research and theory* (Vol. 2, pp. 89–195). New York: Academic Press

Baddeley, A.D. (2000). The episodic buffer: a new component of working memory *Trends in Cognitive Sciences*, *4*(11), 417–423.

Baddeley, A.D., & Hitch, G.J. (1974). Working Memory. In G. Bower (Ed.), *The psychology of learning and motivation* (pp. 47–89). New York: Academic Press.

Baddeley, A.D., Eysenck, M.W., & Anderson, M. (2009). *Memory* (p. 451). Psychology Press.

Baddeley, A.D., & Allen, R., Hitch, G.J. (2010). Investigating the episodic buffer. *Psychologica Belgica*.

Bliss, I., & Hämäläinen, H. (2005). Different working memory capacity in normal young adults for visual and tactile letter recognition task *Scandinavian Journal of Psychology*, *46*(3), 247–251. doi:10.1111/j.1467-9450.2005.00454.x

Bliss, I., Kujala, T., & Hämäläinen, H. (2004). Comparison of blind and sighted participants' performance in a letter recognition working memory task. *Cognitive Brain Research*, *18*(3), 273–277. doi:10.1016/j.cogbrainres.2003.10.012

Bliss, J., Crane, H., & Mansfield, P. (1966). Information available in brief tactile presentations. *Perception & Psychophysics*, *1*, pp. 273-283.

Bowers, R.L., Mollenhauer, M.S., & Luxford, J. (1990). Short-term memory for tactile and temporal stimuli in a shared-attention recall task *Perceptual and motor skills*, *70 (*3 Pt 1), 903–913.

Brady, T.F., Konkle, T., Alvarez, G.A., & Oliva, A. (2008). Visual long-term memory has a massive storage capacity for object details *Proceedings of the National Academy of Sciences of the United States of America*, *105*(38), 14325–14329. doi:10.1073/pnas.0803390105

Broadbent, D.E. (1958). *Perception and communication* (p. 338). New York: Pergamon Press.

Burton, H., Sinclair, R. J., & Dixit, S. (2010). Working memory for vibrotactile frequencies: Comparison of cortical activity in blind and sighted individuals. *Human Brain Mapping*, NA–NA. doi:10.1002/hbm.20966

Bushnell, E.W., & Baxt, C. (1990). Children's Haptic and Cross-Modal Recognition With Familiar and Unfamiliar Objects. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(6), 1867–1881.

Cohen, H., Scherzer, P., Viau, R., Voss, P., & Lepore, F. (2011). Working memory for braille is shaped by experience *Communicative & integrative biology*, *4*(2), 227–229. doi:10.4161/cib.4.2.14546

Cohen, H., Voss, P., Lepore, F., & Scherzer, P. (2010). The nature of working memory for Braille *PLoS ONE*, *5*(5), e10833–. doi:10.1371/journal.pone.0010833

Coltheart, M. (1980). Iconic Memory and Visible Persistence. *Perception & Psychophysics*, *27*(3), 183–228.

Conrad, R., & Hull, A.J. (1968). Input Modality and the Serial Position Curve in Short-Term Memory. *Psychonomic Science*, *10* (4), pp. 135-136.

Cowan, N. (1984). On Short and Long Auditory Stores. *Psychological Bulletin*, *96*(2), 341–370.

Craik, F., & Lockhart, R. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior*, *11*(6), 671–684. doi:10.1016/S0022-5371(72)80001-X

Darwin, C., Turvey, M.T., & Crowder, R. (1972). An auditory analogue of the Sperling partial report procedure: Evidence for brief auditory storage. *Cognitive Psychology*, *3*, 255–267.

Easton, R., Greene, A., & Srinivas, K. (1997). Transfer between vision and haptics: Memory for 2-D patterns and 3-D objects. *Psychonomic Bulletin & Review*, *4*(3), pp. 403-410.

Ebbinghaus, H. (1913). *Memory: A contribution to experimental psychology.* New York: Teacher's College. (original work published in 1885).

Fernandes, A.M. & Albuquerque, P.B. (submitted). Tactual perception: A review of experimental variables and procedures.

Gallace, A., & Spence, C. (2008). The cognitive and neural correlates of "tactile consciousness": A multisensory perspective. *Consciousness and Cognition*, *17*(1), 370–407. doi:10.1016/j.concog.2007.01.005

Gallace, A., & Spence, C. (2009). The Cognitive and Neural Correlates of Tactile Memory. *Psychological Bulletin*, *135*(3), 380–406. doi:10.1037/a0015325

Gallace, A., Tan, H.Z., Haggard, P., & Spence, C. (2008). Short term memory for tactile stimuli. *Brain Research*, *1190*, 132–142. doi:10.1016/j.brainres.2007.11.014

Gilson, E.Q., & Baddeley, A.D. (1969). Tactile short-term memory. *Quarterly Journal of Experimental Psychology*, *21*(2), 180–184.

Giudice, N.A., Betty, M. R., & Loomis, J.M. (2011). Functional equivalence of spatial images from touch and vision: Evidence from spatial updating in blind and sighted individuals *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *37*(3), 621–634. doi:10.1037/a0022331

Holtby, R. & D'angiulli, A. (August, 2011). The effects of interference on recognition of haptic pictures in blindfolded sighted participants: The modality of representation of haptic information. Poster presented at the 5th International Conference on Memory (ICOM5), York, UK.

Kiphart, M.J., Auday, B.C., & Cross, H.A. (1988). Short-term haptic memory for three-dimensional objects. *Perceptual and motor skills*, *66*(1), 79–91.

Kiphart, M.J., Hughes, J., Simmons, J., & Cross, H.A. (1992). Short-term haptic memory for complex objects. *Bulletin of the Psychonomic Society*, *30*(3), 212–214.

Klatzky, R.L., Lederman, S.J., & Metzger, V. (1985). Identifying Objects by Touch - an Expert System. *Perception & Psychophysics*, *37*(4), 299–302.

Lacey, S., & Campbell, C. (2006). Mental representation in visual/haptic crossmodal memory: evidence from interference effects. *Q J Exp Psychol (Colchester)*, *59*(2), 361–376. doi:10.1080/17470210500173232

Manning, S.K. (1980). Tactual and visual alphanumeric suffix effects. *The Quarterly Journal of Experimental Psychology*, *32*(2), 257–267. Taylor & Francis. doi:10.1080/14640748008401162

McGlone, F., Vallbo, A.B., Olausson, H., Loken, L., & Wessberg, J. (2007). Discriminative touch and emotional touch. *Can J Exp Psychol*, *61*(3), 173–183.

Miles, C., & Borthwick, M. (1996). Tactile short-term memory revisited *Memory*, *4*(6), 655–668.

Millar, S. (1972). Effects of interpolated tasks on latency and accuracy of intramodal and cross-modal shape recognition by children *Journal of Experimental Psychology, 96*(1), 170–175. doi:10.1037/h0033546

Millar, S. (1974). Tactile Short-Term Memory by Blind and Sighted Children. *British Journal of Psychology*, *65*(2), 253–263. doi:10.1111/j.2044-8295.1974.tb01399.x

Millar, S. (1975). Effects of tactual and phonological similarity on the recall of Braille letters by blind children. *British Journal of Psychology*, *66*(2), 193–201. doi:10.1111/j.2044-8295.1975.tb01455.x

Millar, S. (1999). Memory in touch. *Psicothema*, *11*, pp. 747-467.

Murray, D.J., Ward, R., & Hockley, W.E. (1975). Tactile short-term memory in relation to the two-point threshold. *Quarterly Journal of Experimental Psychology*, *27*(2), 303–312. Taylor & Francis. doi:10.1080/14640747508400489

Nabeta, T. & Kusumi, T. (2007). *Memory capacity for haptic common objects,* Unpublished manuscript, Kyoto University, Japan.

Neisser, U. (1967). *Cognitive Psychology* (1st ed. p. 351). New York: Appleton - Century - Crofts.

Oberauer, K., & Göthe, K. (2006). Dual-task effects in working memory: Interference between two processing tasks, between two memory demands, and between storage and processing. *European Journal of Cognitive Psychology*, *18*(4), 493–519. doi:10.1080/09541440500423038

Paz, S., Mayas, J., & Ballesteros, S. (2007). Haptic and visual working memory in young adults, healthy older adults, and mild cognitive impairment adults. *Proceedings of the World Haptics.*

Pensky, A.E.C., Johnson, K.A., Haag, S., & Homa, D. (2008). Delayed memory for visual-haptic exploration of familiar objects. *Psychonomic Bulletin & Review*, *15*(3), 574–580. doi:10.3758/PBR.15.3.574

Ricciardi, E., Bonino, D., Gentili, C., Sani, L., Pietrini, P., & Vecchi, T. (2006). Neural correlates of spatial working memory in humans: a functional magnetic resonance imaging study comparing visual and tactile processes. *Neuroscience*, *139*(1), 339–349. doi:10.1016/j.neuroscience.2005.08.045

Schindler, I., Clavagnier, S., Karnath, H.-O., Derex, L., & Perenin, M.-T. (2006). A common basis for visual and tactile exploration deficits in spatial neglect *Neuropsychologia*, *44*(8), 1444–1451. doi:10.1016/j.neuropsychologia. 2005.12.003

Sebastián, M., Mayas, J., Manso, A.J., & Ballesteros, S. (2008). *Working Memory for Visual and Haptic Targets: A Study Using the Interference Paradigm*. (M. Ferre, Ed.)Lecture Notes in Computer Science (Vol. 5024, pp. 395–399). Berlin, Heidelberg: Springer Berlin Heidelberg. doi:10.1007/978-3-540-69057-3_52

Shallice, T., & Warrington, E.K. (1970). Independent functioning of verbal memory stores: A neuropsychological study. *The Quarterly Journal of Experimental Psychology*, *22*(2), 261–273. doi:10.1080/00335557043000203

Sherrick, C., & Craig, J. (1982). *The Psychophysics of Touch*. (W. Schiff & E. Foulke, Eds.)Tactual Perception: A sourcebook (p. 465). Cambridge University Press.

Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs: General and Applied*, *74*(11), pp. 1-29.

Sullivan, E.V., & Turvey, M.T. (1972). Short-term retention of tactile stimulation *The Quarterly Journal of Experimental Psychology*, *24*(3), 253–261. doi:10.1080/14640747208400278

Sullivan, E., & Turvey, M.T. (1974). On the short-term retention of serial, tactile stimuli. *Memory & Cognition*, *2*(2), 600–606.

Tulving, E., & Craik, F. (2000). *The Oxford Handbook of Memory*. New York: Oxford University Press.

Turvey, M. (1996). Dynamic Touch. *American Psychologist*, *51* (11). pp. 1134-1152.

Unsworth, N., & Engle, R.W. (2007). On the division of short-term and working memory: An examination of simple and complex span and their relation to higher order abilities *Psychological Bulletin*, *133*(6), 1038–1066. doi: 10.1037/0033-2909.133.6.1038

Watkins, M., & Watkins, O. (1974). A Tactile Suffix Effect. *Memory & Cognition*, *2*, 176–180.

Watkins, O., & Watkins, M. (1980). The modality effect and echoic persistence *Journal of Experimental Psychology: General*, *109*(3), 251–278.

Whitaker, T. A., Simões-Franklin, C., & Newell, F.N. (2008). Vision and touch: independent or integrated systems for the perception of texture *Brain Res*, *1242*, 59–72. doi:10.1016/j.brainres.2008.05.037

Wijntjes, M.W.A., van Lienen, T., Verstijnen, I.M., & Kappers, A.M.L. (2008). Look what I have felt: unidentified haptic line drawings are identified after sketching. *Acta Psychologica*, *128*(2), 255–263. doi:10.1016/j.actpsy.2008.01.006

PART I

CONCLUSION

Studies on touch have focused on tactile and haptic perception, and immediate sensory memory. More recently, some authors started to explore longer registers of memory in touch, as well as applying neuropsychological approaches to haptics.

Through these reviews it was possible to enunciate several variables that are central in the field of haptics, such as the nature of the stimuli, the selected participants, and the exploration conditions. As it was possible to observe, these variables are determinant in tactual performance and the conclusions and implications of these empirical studies should always attend to the specificity of the chosen designs. The experimental option for task conditions similar to everyday haptic interactions with objects (implying free exploration and everyday objects) seem to be optimal conditions for haptic testing, and research designs must be improved to allow a high experimental control in this conditions.

The role of crossmodal and multisensory interaction of touch with other senses was considered. Our everyday experience is mainly composed by simultaneous inputs from more than one sensory modality. We usually touch and see an object at the same time, and we can explore its sounds as we manipulate it. Also, vision frequently guides our haptic exploration, detecting the items we wish to explore, mediating grasping and assisting the hands while we explore the objects. Nonetheless the relevance of multisensory stimulation, studying how we perceive and encode stimuli when information of just one sensory modality is available, allows us to understand how we integrate information from various sources, and also how modality-specific information is processed.

Finally, an analysis of previous research on touch and memory was conducted, attending to research on immediate sensory memory, short-term and working memory and long-term memory. Most studies to this date have focused on memory registers like immediate sensory memory. Working memory has been explored more recently and long-term memory studies in touch are scarce. Haptic memory seems to show a modality specificity, with verbal, visual and spatial cues not being sufficient to explain the data obtained in tasks in which stimuli are presented through touch only.

Future research on memory for touch should attend to the knowledge on the effects of the previously described central variables in touch when designing experiments and when selecting a research topic. More research on memory for touch is needed, specifically regarding working memory and long term memory storages, that have not been explored in previous works.

Nova teoria

Uma nova teoria reposiciona o pormenor (ou mesmo o insignificante) tornando-o centro. Tudo aquilo que é pequeno pode ser posicionado de modo a que aos nossos olhos pareça grande. (...)

Gonçalo M. Tavares*, em Breves notas sobre ciência*

PART II

INTRODUCTION

The term working memory was used for the first time in 1960 within the metaphor of the mind as a computer, referring to a type of memory necessary to perform an ongoing task (Miller, Galanter, & Pribram, 1960). This concept was often used in memory research in the 1960s and Atkinson and Shriffin's (1968) memory model used this concept to refer to a short-term memory division in memory. Nowadays, the concept of working memory is intrinsically associated with Baddeley and Hitch's (1974) working memory model. Within this model, working memory is a dynamic (division of) memory, that comprises the notions of short-term and immediate memory, but also presents complex processes of reasoning and attentional capacity that allow us to do complex tasks as reading or calculating.

Few researchers have explored the theme of working memory within touch. Designing experiments on touch is a complex process and frequently demands an elaborate adaptation of classical procedures used in vision and audition. Moreover, movements are a crucial aspect in haptic recognition (Lederman & Klatzky, 1987) and allowing participants to haptically explore the objects implies a great increase in stimuli presentation rates. Klatzky, Lederman, and Metzger (1985) showed that participants needed around three seconds to correctly identify an object presented by touch alone, and considering that the process of placing and removing haptic stimuli from the participants hands has to be manually executed by the experimenter, the inter-stimuli interval can easily take as long as five seconds.

Published studies on haptic working memory mostly focus on evaluations of performance of healthy and cognitive impaired adults (e.g., Ballesteros, 2004; Paz, Mayas, & Ballesteros, 2007; Yang, Ogasa, Ohta, Abe, & Wu, 2010); neuropsychological approaches to tactile working memory (e.g., Hannula et al., 2010; Kaas, van Mier, & Goebel, 2006; Savolainen et al., 2011); or comparisons of performance with tactile and visual stimuli (e.g., Bliss, Kujala, & Hämäläinen, 2004; Dalton, Lavie, & Spence, 2009; Sebastián, Julia Mayas, Manso, & Ballesteros, 2008).

To our knowledge, no published work has directly and systematically explored the theme of working memory in touch, specifically with everyday objects.

The purpose of the experiments presented in this second part of the thesis are twofold: we intended to evaluate separately the impact of five types of interference in haptic working memory for common objects (first study) and uncommon objects (second study), but also, we intended to explore the patterns of interference in relation to object type (third study) and to do this we reanalysed the same data presented on the previous studies with a new approach that resulted in a direct comparison between common and uncommon objects for each type of interference task. This last study represents a different perspective on the same data, that allowed us to further explore the interpretation of the data on haptic recognition under interference effects.

REFERENCES

Atkinson, R., & Shiffrin, R. (1968). Human memory: A proposed system and its control processes. In K. Spence (Ed.), *The psychology of learning and motivation: advances in research and theory* (Vol. 2, pp. 89–195). New York

Baddeley, A.D., & Hitch, G.J. (1974). Working Memory. In G. Bower (Ed.), *The psychology of learning and motivation* (pp. 47–89). New York: Academic Press.

Ballesteros, S. (2004). Intact haptic priming in normal aging and Alzheimer's disease: evidence for dissociable memory systems. *Neuropsychologia*, *42*(8), 1063–1070. doi:10.1016/j.neuropsychologia.2003.12.008

Bliss, I., Kujala, T., & Hämäläinen, H. (2004). Comparison of blind and sighted participants' performance in a letter recognition working memory task. *Cognitive Brain Research*, *18*(3), 273–277. doi:10.1016/j.cogbrainres.2003.10.012

Dalton, P., Lavie, N., & Spence, C. (2009). The role of working memory in tactile selective attention *Quarterly Journal of Experimental Psychology*, *62*(4), 635–644. doi:10.1080/17470210802483503

Hannula, H., Neuvonen, T., Savolainen, P., Hiltunen, J., Ma, Y.-Y., Antila, H., Salonen, O., et al. (2010). Increasing top-down suppression from prefrontal cortex facilitates tactile working memory *NeuroImage*, *49*(1), 1091–1098. doi: 10.1016/j.neuroimage.2009.07.049

Holtby, R. & D'angiulli, A. (August, 2011). The effects of interference on recognition of haptic pictures in blindfolded sighted participants: The modality of representation of haptic information. Poster presented at the 5th International Conference on Memory (ICOM5), York, UK.

Kaas, A. L., van Mier, H., & Goebel, R. (2006). The Neural Correlates of Human Working Memory for Haptically Explored Object Orientations. *Cerebral Cortex*, *17*(7), 1637–1649. doi:10.1093/cercor/bhl074

Klatzky, R., Lederman, S., & Metzger, V. (1985). Identifying Objects by Touch - an Expert System. *Perception & Psychophysics*, *37*(4), 299–302.

Lederman, S., & Klatzky, R. L. (1987). Hand movements: a window into haptic object recognition *Cognitive Psychology*, *19*(3), 342–368.

Miller, G., Galanter, E., & Pribram, K. (1960). *Plans and the Structure of Behavior.* New York: Holt, Rinehart & Winston.

Paz, S., Mayas, J., & Ballesteros, S. (2007). Haptic and visual working memory in young adults, healthy older adults, and mild cognitive impairment adults. *Proceedings of World Haptics Conference.*

Savolainen, P., Carlson, S., Boldt, R., Neuvonen, T., Hannula, H., Hiltunen, J., Salonen, O., et al. (2011). Facilitation of tactile working memory by top-down suppression from prefrontal to primary somatosensory cortex during sensory interference *Behavioural brain research*, *219*(2), 387–390. doi:10.1016/j.bbr.2011.01.053

Sebastián, M., Mayas, Julia, Manso, A. J., & Ballesteros, S. (2008). *Working Memory for Visual and Haptic Targets: A Study Using the Interference Paradigm*. (M. Ferre, Ed.)Lecture Notes in Computer Science (Vol. 5024, pp. 395–399). Berlin, Heidelberg: Springer Berlin Heidelberg. doi:10.1007/978-3-540-69057-3_52

Wijntjes, M. W. A., van Lienen, T., Verstijnen, I. M., & Kappers, A. M. L. (2008). Look what I have felt: unidentified haptic line drawings are identified after sketching. *Acta Psychologica*, *128*(2), 255–263. doi:10.1016/j.actpsy.2008.01.006

Yang, J., Ogasa, T., Ohta, Y., Abe, K., & Wu, J. (2010). Decline of Human Tactile Angle Discrimination in Patients with Mild Cognitive Impairment and Alzheimer's Disease. *Journal of Alzheimers Disease*, *22*(1), 225–234. doi:10.3233/JAD-2010-100723

PART II

INTERFERENCE TASKS: Experimental Work

Haptic recognition of common objects:
The effects of interference at encoding[3]

ABSTRACT

The present work reports the results of an experiment on haptic memory of common objects. This study intended to explore how haptic information is encoded in memory. Participants interacted with a set of 50 common objects under single- or dual-task conditions. Participants then performed an immediate, incidental haptic recognition memory test with 25 presented and 25 non-presented objects. During the experiment, the participants did not had visual contact with the objects and were instructed to touch each object with one hand for three seconds. The dual-task condition consisted of the simultaneous performance of the haptic study test and one of the following types of interference task: motor (movements with one hand), haptic (evaluating similarities between paper samples), verbal (evaluating similarities between pseudowords), or visuospatial (evaluating similarities between abstract three-dimensional forms).

The results demonstrated that haptic recognition of studied common objects was robust and that only haptic interference during encoding could impair haptic recognition. The results are herein discussed in the context of the working memory model (Baddeley & Hitch, 1974; Baddeley, 2000; Baddeley, Allen, & Hitch, 2010).

In 1974, Baddeley and Hitch proposed a working memory model, which suggested that apprehended stimuli would be encoded through a multicomponent working memory system, regardless of the perceptual modality in which they were perceived. This system was composed of a *central executive*, which was responsible for information processing and attentional control, and two subcomponents: a *phonological loop*, which processed verbal and auditory information, and a *visuospatial sketchpad*, which processed visual and spatial information. A new subcomponent, the *episodic buffer*, was included in the model and was suggested to manage multimodal codes and to be responsible for the integration of information from the other two subcomponents (Baddeley, 2000). More recently, the episodic buffer has been conceptualised as having a more passive role, where it serves as a storage unit for information that has been merged and integrated by the other two subcomponents (Baddeley et al., 2010). This is one of the most popular working memory models and has been shown to be robust in many tasks and paradigms, mainly with visual or auditory stimulation, through the recollection of words or phrases (verbal), and visuospatial abstract stimuli (Baddeley, 2001; 2003).

As stated by this model, haptic or tactile information should be perceived and transformed into a visuospatial or verbal code so that it can be processed and subsequently stored in long-term memory. However, other authors have suggested the need to incorporate modality specificity into memory models to

---

[3] Paper submitted to *Memory & Cognition*

account for all types of stimuli, and this is thought to be particularly important for immediate or sensory memory (Atinkson & Schiffrin, 1968; Neisser, 1967; Sperling, 1960). In Baddeley and Hitch's (1974; Baddeley, 2000) working memory model, connections can be drawn between the visuospatial sketchpad and visual stimuli as well as between the phonological loop and auditory stimuli. As such, an assumption that can be drawn from this model is that stimuli involving touch, taste and smell could also be processed by other specific subcomponents in working memory. Kaas, Stoeckel and Goebel (2008) hypothesized that a *tactual buffer* exists in working memory. The authors referred to previous experiments on haptic and tactile memory, which did not consider memory for particular haptic features, such as temperature, but instead relied on stimuli with strong verbal or visual codes. As such, these previous experiments did not provide clear conclusions about how haptic stimuli are processed. However, although multimodal strategies are generally more common than unimodal strategies, Kaas et al. (2008) proposed that specific haptic features have a working memory representation. These hypothesis seems reasonable, considering that touch-specific codes could be attended to even when multimodal codes are unavailable (i.e., when encoding touch-specific features, such as temperature or relief).

Before reviewing the literature on memory for touch, a conceptual distinction must be made between *tactile* and *haptic* cognition. Tactile cognition is associated with passive touch, while haptic cognition entails an active exploration of stimuli and frequently involves free manipulation (Loomis & Lederman, 1986). In this way, everyday experiences with touch are almost exclusively haptic, providing tactile information about objects and kinesthetic cues from exploratory movements. Purely tactile perception tends to occur only under experimental conditions during the presentation of stimuli, such as vibration, and without any intentional manipulation by the participant. Research on haptic exploration usually implies a smaller degree of control, as presentation times need to be longer and as object exploration typically involves some amount of individual variation although clear general patterns of movement can be detected across participants (Lederman & Klatzky, 1987).

Memory for touch has been explored in short-term memory studies using tactile passive stimuli (e.g., vibrations). These studies have produced inconsistent results regarding forgetting. In fact, some experiments have shown decay functions in tactile memory (Gilson & Baddeley, 1969; Miles & Borthwick, 1996), while others have not (Sullivan & Turvey, 1972). Using more complex stimuli (geometrical plastic objects), Kiphart, Auday, and Cross (1988) found no decay function for haptic memory. However, subsequent studies measuring sensitivity (*d'*) have suggested the existence of decay (Kiphart, Hughes, Simmons, & Cross, 1992). For complex stimuli (three-dimensional nonsense shapes), a study with blind and sighted children by Millar (1974) found a decay function for touch. These data suggest that modality specificity may be relevant for memory and that encoding may be determined by the perceptual properties of each modality. For touch, the long perceptual trace provided by the mechanoreceptors may function to change the way that stimuli are encoded.

Studies on longer memory registers have suggested that haptic memory for everyday objects can retain a large number of items (Nabeta & Kusumi, 2008). In a study with everyday objects, Nabeta and Kusumi

(2008) reported that haptic recognition was identical for lists of 100 or 500 objects. Following a comparison between haptic and visual performance, these authors argued in favor of a haptic-specific system that could justify the perceived haptic advantage, which was based on the greater sensitivity rates for the haptic condition compared to the visual condition. Lacey and Campbell (2006) also reported differences between touch and vision in a crossmodal study with familiar and unfamiliar objects involving different interference conditions at encoding and retrieval. Although these authors did not present a congruent modality condition, there were differences in accuracy between visual-haptic and haptic-visual recognition rates after interference during encoding, which suggested that modality-specific properties mediated the recognition of the stimuli.

As stated, previous research has indicated that processes supporting tactile memory may be distinct from processes that support other sensory modalities, which was previously advocated by Klatzky and Lederman (1987) regarding experiments on tactile perception. Considering the inconsistencies concerning forgetting in short-term tactile memory (Gilson & Baddeley, 1969; Sullivan & Turvey, 1972) and the differences in performance depending on the particular sensory modality (Lacey & Campbell, 2006; Nabeta & Kusumi, 2008), these results from tactile memory research cannot be completely explained by a modality-independent general memory model. In spite of these previous data, no adjustments were made in Baddeley and Hitch's (1974) working memory model to include a touch-specific subcomponent, although Baddeley (1999) admitted the possibility of adding subcomponents to the model and presented the episodic buffer as a new subcomponent (Baddeley, 2000). Haptic and tactile memory need to be further explored to elaborate on the touch-specific subsystem of working memory.

In an analysis of memory in touch, Millar (1999) argued that memory models involving touch need to present a flexible system that allows for the integration of long-term memory, self-reference information that is associated with the spatial frames of object exploration, procedural knowledge, and visuospatial information. Such a model should include a procedural loop system that would be responsible for encoding and rehearsing the movements involved in the exploration of objects. Millar (1999) discussed the possibility that a central executive system could be responsible for this type of integrated knowledge concerning touched objects. However, this raises doubt how such a system could maintain a constant actualisation for acquired information and experiences. In this context, the introduction of the episodic buffer (Baddeley, 2000) appears to clarify these integration processes and makes the revised working memory model more congruent for tactile cognitive demands, but only when we also hypothesize the existence of a tactile subcomponent as well. However, a recent analysis of the episodic buffer has suggested the existence of a more passive subcomponent (Baddeley et al., 2010). Binding appeared to occur not in the episodic buffer, as was suggested initially (Baddeley, 2000), but in the visuospatial sketchpad and the phonological loop. The tasks of the episodic buffer are limited to the recovery, storage and creation of awareness regarding the integrated information.

Few studies have explored haptic memory tasks using everyday objects, and haptic research has typically involved crossmodal paradigms and has compared haptic and visual performance in recognition and identification tasks (Bushnell & Baxt, 1999; Craddock & Lawson, 2008; Lacey & Campbell, 2006). This scarcity of studies, as well as their empirical option for the comparison between sensory modalities, may justify why memory for touch has not been sufficiently explored and understood and may also be one of the reasons why haptics is not yet considered in memory theoretical models.

This paper contributes to this discussion about the nature of tactile memory and has analysed data according to the model of working memory (Baddeley, 2000; Baddeley & Hitch, 1974). We explored the theoretical relevance of a touch-specific memory storage in the comprehension of tactile processing at early stages. Specifically, following a study phase with haptic encoding of a set of common objects, the participants performed an immediate, incidental haptic recognition memory task. Using a dual-task paradigm, the effect of four interference tasks during encoding was explored and compared to the participants' performance in single-task condition. Following the scope of Baddeley and Hitch's (1974) working memory model, verbal and visuospatial interference tasks were included. However, to access the potential specificity of haptic memory, tactile and motor interference tasks were also incorporated.

METHOD

Participants

Seventy-five undergraduate and graduate students volunteered to participate in the experiment; these included 18 males and 57 females with a mean age of 23.2 years (*SD* = 6.8 years).

Materials and Stimuli

The materials that were used for the experiments included a wooden box (with an opening facing the participant, which was covered by a cotton cloth, and another facing the experimenter) and was internally divided in half with cardboard; headphones, which produced white noise; and a computer screen that was placed on top of the wooden box and was used to present verbal and visuospatial stimuli for the interference tasks.

The haptic task consisted of touching 50 common objects that were randomly selected from a pool of 92 objects (see Appendix). The pool of stimuli was constructed according to the following criteria: the objects had to be sufficiently small to allow for exploration with one hand, the objects had to enable silent exploration, and objects had to be common or familiar. By previous studies, the 92 objects were evaluated for familiarity using a five-point Likert scale (where *one* was defined as *an object I never use or use less than once a year*, and *five* was defined as *an object I use every day or almost every day*), and the objects had a mean familiarity evaluation of 3.54 (*SD* = 0.53). The objects were also evaluated for correct identification (*M* = 83%, *SD* = 3%).

In these previous studies, the participants had blindly touched the objects with one hand for three seconds each and then emitted a response for familiarity and identification.

The haptic interference task involved the evaluation of pairs of paper samples. Various types of paper were presented (e.g., white, recycled, magazine, newspaper, photo), and each pair was attached to a piece of cardboard (14.8 cm x 21.0 cm) that was divided lengthwise by a sponge (1 cm x 21.0 cm). "Same" pairs presented the same paper on both parts of the cardboard, and "different" pairs presented different paper samples. These were organised pseudo-randomly; for 52 types of paper, 52 "same" stimuli pairs and 54 "different" stimuli pairs were created. Preliminary studies assured that the participants were able to distinguish each of the "different" pairs (c.f. Appendix C).

The verbal interference task stimuli consisted of trisyllabic pseudo-word pairs. The pseudo-words were selected from the work of Pureza (2009). "Same" pairs consisted of pseudo-words with identical syllables in a different order for each pseudo-word (e.g., TA-FA-LE / FA-LE-TA), and "different" pairs were composed of pseudo-words with two different syllables (e.g., NO-SI-NE / NI-NE-SO). Syllable variation was obtained by swapping either a vowel or consonant within the pseudo-word from one syllable to another (half of the pairs had a vowel swap and the other half had a consonant swap). Pilot studies had shown that participants were able to read and evaluate the two pseudo-words in a three-second presentation time with a correct response rate above chance (c.f. Appendix D).

The visuospatial interference was designed according to the three-dimensional abstract forms of Shepard and Metzler (1971). "Same" pairs were composed of a 40-degree rotation from one figure to the other, and "different" pairs were composed of a 40-degree mirror image rotation from one figure to the other. For the dual-task conditions, preliminary studies with these stimuli had shown that participants were only able to perform above chance (c.f. Appendix B) with the 40-degree rotations. Rotations of a greater degree cause the visuospatial tasks to be too difficult to perform during the three-second presentations.

Design

The 75 participants were randomly distributed across five experimental conditions, which included one condition without interference and four conditions with different interference tasks. The interference tasks were of the motor, haptic, verbal, and visuospatial type.

The participants in the condition without interference performed the study with 50 objects, which were randomly presented for three seconds each, and performed an immediate, incidental haptic recognition memory task with 25 old and 25 new objects that were randomly presented for three seconds each. For this task, the participants were instructed to orally answer whether each object was presented during the study phase. The objects were directly placed into the participants' non-dominant hand.

Participants in dual-task conditions performed the haptic study phase and one of the four interference tasks simultaneously (motor, haptic, verbal and visuospatial). Each one of the four interference tasks were performed twice; they were performed once in single-task condition and once simultaneously with the haptic study. The performance in interference single-task condition established a baseline for performance in each interference task and allowed for the examination of potential tradeoff effects when performing the two tasks simultaneously. Presentation order was counterbalanced among the participants. As such, participants in haptic, verbal and visuospatial interference conditions took part in three distinct phases of the experiment: the single interference task, the simultaneous interference task and haptic study phase, and an incidental immediate haptic recognition memory task. Note that to maintain an equivalent retention interval for all the conditions (no interference and interference conditions), the haptic recognition test was presented immediately following the haptic study phase in every condition. Motor interference was conducted only simultaneously with the haptic task, as this task did not demand a specific response from the participants (only the execution of movements), a performance measure was not available.

Procedure

The participants sat on an adjustable stool in front of a table where the experimental setup was placed. The participants wore headphones and, after seeing the inside of the empty box, were instructed to slide their hands into each side of the cardboard.

At the beginning of the experiment, participants in the no-interference condition had six training trials for the haptic task. Participants in the interference conditions performed six trials of the given interference task alone and an additional six trials of the interference task plus the haptic task. The training phase allowed participants in the haptic and motor interference tasks to perfectly synchronise the movements of the two hands. During the task, the experimenter was able to watch the movements.

The experiment lasted approximately 30 minutes for the no-interference and motor-interference conditions and 45 minutes for the haptic, verbal, and visuospatial conditions. Although the whole duration of the experiment differed, the study phase and recognition phase times, as well as the retention intervals are exactly the same in all conditions.

The haptic study procedure consisted of touching 50 randomly presented common objects with the non-dominant hand for three seconds each. Sound cues to initiate and end the object exploration were provided through the headphones. Immediately following the haptic study phase, the participants performed an incidental recognition memory task where they touched 25 old objects and 25 new objects in random order. The participants responded to the haptic recognition task by indicating whether each object had been previously touched, and they were instructed to respond as quickly and promptly as possible.

For the dual-task conditions, the interference task was synchronised with the haptic study phase. As such, the stimuli pairs of the interference tasks were presented for three seconds and an answer from the participants was required immediately following their removal. The interference stimuli were presented simultaneously with the touched objects, and the participants haptically explored the everyday objects while evaluating the interference stimuli pairs.

The haptic interference task consisted of evaluating pairs of paper samples. The participants were instructed to explore the objects with their non-dominant hands and to perform the haptic interference task with their dominant hand. The non-dominant hand was positioned in the bottom of the box, palm facing up, and the dominant hand was placed at the top of the box, palm facing down. After the first sound cue, each participant moved both hands. The non-dominant hand freely explored the object while the dominant hand was lowered to the bottom of the box where a paper sample pair was placed. The participants then explored both paper samples at the same time with the tips of their fingers. After the second sound cue, the participants ceased their exploration and were asked to orally state whether they believed the two paper samples were of the same type of paper.

The motor interference task required participants to perform the same movements as previously described for the haptic interference task, but to do so without evaluating a paper sample pair. As there were no paper samples were presented in the box, the participants needed to lower their dominant hand and rub the bottom of the wooden box, while freely exploring the objects with their non-dominant hand. For this task, no answer was required. The execution of movements was controlled by the experimenter, who was able to see the participant's hands.

The verbal interference task involved the evaluation of trisyllabic pseudo-word pairs according to the composition of their syllables. The participants were asked to haptically explore objects with their non-dominant hand as their dominant hand rested on the inside of the box. The pseudo-word pairs were presented on the computer screen that was placed at eye-level on the wooden box at a distance of approximately 60 cm from the participant. Each pseudo-word pair was presented on the screen for three seconds. As the participants explored each object, they were asked to read the pseudo-words out loud. Afterwards, the words were removed from the screen, and the participants were asked to state whether they believed the two words had exactly the same syllables.

The visuospatial interference task involved the mental rotation of abstract three-dimensional forms (Shepard & Metzler, 1971). As they haptically explored objects with their non-dominant hand, the participants visualised a pair of figures on the computer screen, which was placed on the box at a distance of approximately 60 cm. The dominant hand remained inside of the box in a resting position. After a three-second presentation, the stimuli on the screen were removed, and the participants were asked to state whether they believed the two figures represented different views of the same form.

RESULTS

The present experiments confirmed the expertise of touch (Klatzky, Lederman & Metzger, 1985) and its robustness in memory tasks (Nabeta & Kusumi, 2008).

By analysing the overall recognition rate performance in each task (correct answers: hits plus correct rejections) and performing t-tests, we found haptic recognition to be better than chance (>.50) for every condition, which suggested a good level of discriminability. The single haptic study condition had a correct answer rate of .92 (*SD* = .01; *t* (14) = 5377.2, *p* < .001); the motor condition had a correct answer rate of .93 (*SD* = .01; *t* (14) = 4453.7, *p* < .001); the verbal interference had a correct answer rate of .87 (*SD* = .03; *t* (14) = 1842.5, *p* < .001); the visuospatial interference had a correct answer rate of .85 (*SD* = .02; *t* (14) = 2018.2, *p* < .001); and the haptic interference had the lowest performance rate of .76 (*SD* = .03; *t* (14) = 1869.1, *p* < . 001). Although the correct answer proportions can be useful for generating an overall pattern of results, the corrected hits (hits minus false alarms) allowed for an improved analysis of the results. Figure 1 shows the values of haptic recognition for correct responses and for corrected hits in the five conditions.

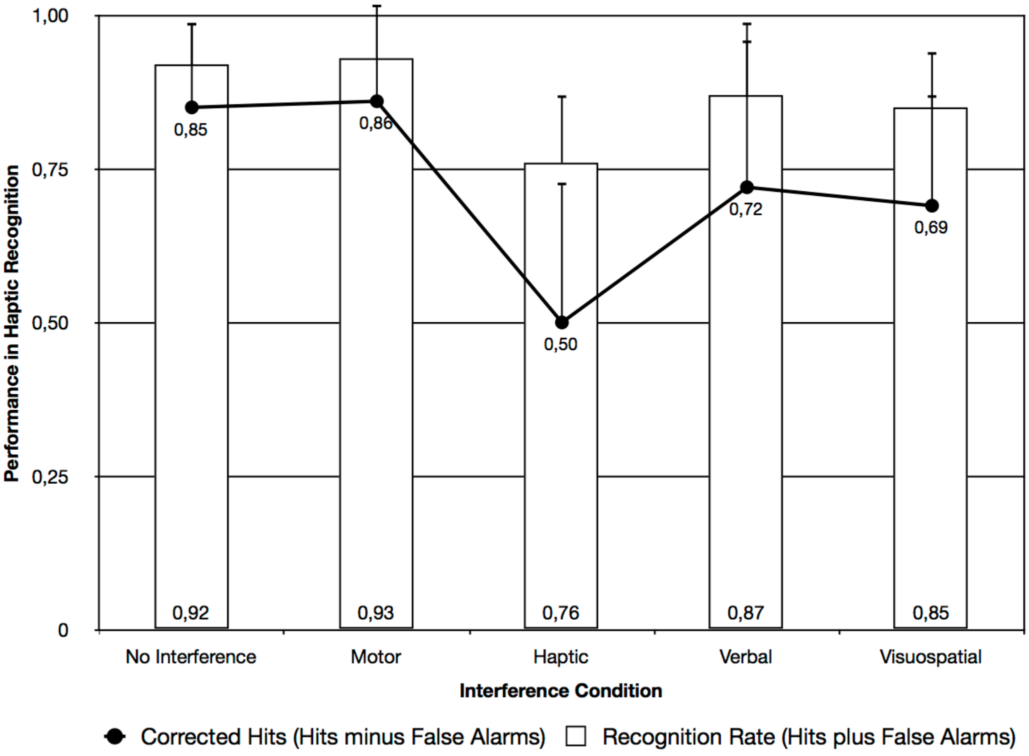

Figure 1: Recognition rate (hits plus correct rejections) and corrected hits (hits minus false alarms) for haptic recognition of common objects according to interference condition

The accuracy (hits minus false alarms) of the participants for haptic recognition was high for each condition. A one-way ANOVA on the accuracy of haptic recognition revealed a main effect of the interference task (*F* [4, 33.5] = 11.78, *p* < .001, r = .628). The post-hoc tests found that the correct hits for haptic recognition in motor conditions (*M* = .86, *SD* = .08) and control conditions (*M* = .85, *SD* = .08) were equivalent, and this suggested that simultaneous movements could not disturb the encoding of the haptic stimuli. The visuospatial (*M* = .69, *SD* = .20) and verbal (*M* = .72, *SD* = .21) interference conditions had no impact on the participants' haptic recognition performance, as was shown by the equivalent results for these conditions and the control condition. Only haptic recognition following haptic interference (*M* = .50, *SD* = .21) was significantly different from haptic recognition without interference. Furthermore, it is noteworthy that the haptic and verbal interference, as well as the haptic and visuospatial interference conditions, were not found to differ in haptic recognition performance. As expected, this result suggests that both spatial and verbal encoding are relevant elements of haptic memory for common objects.

The values for B''_D (Donaldson, 1996) were calculated as an accuracy measure. Donaldson (1996) presents this value as a good evaluation of accuracy in memory tasks, taking into consideration hits and false alarms. B''_D values ranges from -1 to 1, with negative values revealing liberal criteria and positive values showing more conservative ones. The analysis revealed that there were no differences in the criteria for the interference conditions (*F* [4, 74] = 0.91, *p* = .463, r = .222), which suggests that participants maintained similar criteria for the presented items in all conditions. The mean B''_D values were 0.21 (*SD* = .47) for the no-interference condition, -0.01 (*SD* = .55) for the motor interference condition, 0.25 (*SD* = .50) for the haptic interference condition, 0.06 (*SD* = .36) for the verbal interference condition, and 0.10 (*SD* = .48) for the visuospatial interference condition.

The final analysis concerned the participants' performance on the interference tasks only. We examined their performance in the haptic, verbal and visuospatial conditions only, as the motor interference did not demand any response from the participants. As previously mentioned, each participant in the haptic, verbal, and visuospatial interference conditions performed the interference task twice (once in the single condition and once in the dual-task condition). Table 1 shows the mean values and the standard deviations for performance in each interference task.

Table 1: Corrected hits values for haptic, verbal, and visuospatial interference tasks in single- and dual-task conditions for common objects (standard deviations are presented between brackets)

	Haptic Interference Task	**Verbal Interference Task**	**Visuospatial Interference Task**
Single-Task Condition	.51 (.12)	.69 (.25)	.56 (.35)
Dual-Task Condition	.54 (.10)	.68 (.22)	.52 (.31)

The corrected hits for the interference tasks were assessed with a repeated measures 2x3 ANOVA (single- or dual-task presentation condition with haptic study phase x haptic, verbal, or visuospatial interference task). The results revealed no differences in regards to the presentation condition (*F* [1, 42] = 0.07, *p* = .80, r = .045) or the type of task (*F* [2, 42] = 2.27, *p* = .12, r = .311), and there was no interaction effect between these conditions (*F* [2, 42] = 0.49, *p* = .62, r = .152). These results assured that the performance of these interference tasks was equivalent, and suggested that each of the tasks presented a similar level of difficulty. The performance of each task, whether in the single- or dual-task condition, was identical, which indicated that the participants were focused on the interference tasks independent of the haptic study phase.

DISCUSSION

In the present study, neither the verbal nor the visuospatial interference at encoding was able to significantly disrupt the haptic recognition performance, which implies a lesser role of visuospatial sketchpad and phonological loop in haptic processing and recognition. Only a haptic interference task impaired participants' performance in an immediate haptic recognition task. The nature and implications of haptic interference need to be further explored and discussed.

One possible explanation could address the increased difficulty of the haptic exploratory task in the haptic interference condition: participants performed simultaneously distinct movements with the two hands. Nonetheless, data collected within the motor interference condition allows for the rejection of this hypothesis, as the performance of distinct movement sequences did not disrupt participants' haptic recognition memory by itself. Performance in the motor condition was equivalent to the performance with no interference and was clearly different from the haptic interference condition, showing that the haptic interference effect was due to more than motor interference.

Due to dual-task processing, another hypothesis could be based on the fact that haptic interference could be blocking attention or awareness processes and thereby not allowing for the retention of haptic stimuli. In such a scenario, we would expect that responses for haptic recognition memory would be similar to chance (.50). Upon analysis of the present results, we observed that participants were able to recognise everyday objects with a performance greater than chance, as there was a correct responses rate of 0.76 for haptic recognition in the haptic interference conditions.

A theoretical and more complex explanation must also be considered, addressing the explanatory relevance of the episodic buffer for the present results. Baddeley (2000) objected to the idea that the visuospatial sketchpad and the phonological loop are perceptual entities directly associated with vision and audition and suggested that working memory is an independent system that extends beyond perceptual processes. From this perspective, it is possible that the present haptic interference effect could be explained by the binding of verbal and/or visuospatial information. We do not believe that touch can be translated into a blend of information concerning object shape, name, and previous representations in long-term memory. Although haptic recognition in the haptic interference condition was not statistically different from the verbal or visuospatial interference condition, the present data do suggest a tactile/haptic specificity of memory. By using common everyday objects as stimuli, the participants could easily use name encoding (a verbal strategy) or visual imagery (a visual strategy) to support their knowledge of the stimulus presented in the recognition task. Nevertheless, haptic interference was the only task that significantly affected haptic recognition, and this revealed that tactile cues, such as the object's weight, texture, or temperature, were perceived at encoding and were most likely attended to during the recognition phase. Considering these results, we argue in favour of haptic or tactile specificity in working memory.

As mentioned previously (Millar, 1999), an explanatory model for tactile memory needs to account for binding or integration process; this is not only true among perceptual modalities and spatial reference frames, but also for binding of previous representations and long-term memory. The latest conception of the episodic buffer, which posits it to be a passive store that collects and maintains information that is bound either in the visuospatial sketchpad or the phonological loop (Baddeley et al., 2010), is consistent with our present results. Regarding the relevance of spatial encoding for touch and the need to integrate spatial and tactile cues to perform a haptic recognition task, the hypothesis that binding occurs in the visuospatial sketchpad would serve to clarify how the visuospatial and tactile interference conditions appear to be similar in our experiment. Moreover, if tactile and haptic information needed to be connected to spatial cues in the visuospatial sketchpad, this intervention of the sketchpad would justify the equivalence between the haptic and visuospatial interference in haptic recognition. Nonetheless, visuospatial interference did not directly affect the haptic recognition results, as participants may have been attending primarily to haptic and tactile cues.

Likewise, although everyday objects were presented in this study allowing rapid and effective identification, verbal interference by itself did not impair the participants' haptic recognition. Nonetheless, the effects of haptic and verbal interference on haptic recognition were unable to be differentiated. Considering the nature of these stimuli, we can infer that verbal cues play a role in haptic perception and recognition. These stimuli may have elicited, within the phonological loop, the integration of the haptic features of the touched objects with the previous knowledge of the objects. However, these verbal cues alone were not found to be determinant for haptic recognition, as the participants were able to recognise as many objects with verbal interference and without interference.

The nature of the tactile-/haptic-specific component of working memory needs to be further investigated. Millar (1999) referred to this component as a *haptic-movement loop system*, and Kaas et al. (2008) suggested that it could be termed *tactual buffer*. Millar (1999) emphasised the relevance of movement for haptic perception by suggesting that movement allows for the establishment of self-reference and spatial frames for the explored objects. In fact, different movements can be relevant for extracting different properties from touched objects (Klaztzy, Lederman, & Metzler, 1985). Analogous to the articulatory loop, Millar (1999) hypothesised that a touch-specific subcomponent of working memory could be conceptualised as a haptic-movement loop. The following evidence from studies of haptic perception seem to corroborate this view: 1) that movement restrictions can have devastating consequences on haptic perception (Lederman & Klatzky, 2004); 2) that people use specific exploratory procedures to evaluate specific tactile cues (Lederman & Klatzky, 1987); and 3) that previous knowledge about objects drives our exploratory movements and allows for immediate confirmation of object identity (Lederman & Klatzky, 1990). The idea of a tactual buffer (Kaas, et al., 2008), on the other hand, entails the notion of an active storage space for the integration and reorganisation of information, and it appears to be an adequate explanation for tactile/haptic cognition. Merging the various cues that are provided by the tactile senses (i.e., temperature, weight, texture, size, shape, hardness, orientation, position in space) requires an active component for constant updates.

Our results have shown that the simultaneous movement of one hand and the exploration of an object with the other did not impair subsequent haptic recognition. This seems to indicate that a purely movement loop-based hypothesis may need to be discarded. Nonetheless, in the present study, participants touched objects with one hand and performed the interfering movement with the other, and this cannot be disregarded. In addition, the importance of movement during encoding of tactile information is undeniable for the acquisition of cues and the establishment of self-reference frames that allow for a spatial orientation and definition of the object. Nevertheless, the concept of a *movement loop* is complex and cannot be easily separated from tactile information acquisition, as exploratory procedures are determinant for object perception (Lederman & Klatzky, 1987). The restriction of same-hand movements would have a direct impact on the perception of other tactile cues, such as texture or weight, and would make it impossible to directly and independently test movement restriction in haptic memory. Given the simultaneity of the movements performed by both hands and the fact that cues from both hands need to be integrated into working memory, the absence of a motor interference effect may serve as evidence against a purely movement loop-based model and provides evidence against the hypothesis that tactile information is rehearsed as movement.

The conceptualisation of a working memory subcomponent for touch as a tactual buffer (Kaas et al., 2008) appears to provide theoretical and empirical advantages. The tactual buffer takes into account the need to integrate and bind tactile-specific cues, regardless of other modalities, and at the same time allows for a connection with visuospatial, verbal, and long-term memory information through the episodic buffer. This approach would also be helpful for understanding the different results obtained by studies using abstract and concrete stimuli or two- and three-dimensional stimuli in touch. The tactile information that is gathered from touching objects as well as the information that is available from other sources, such as the name, the establishment of a spatial reference frame, or the recollected previous experiences with a stimuli, are crucial to the performance of the participants and could be assimilated with a tactual buffer.

A last thought relates to the working memory model itself. Since the presentation of this model in 1974 (Baddeley & Hitch, 1974), research on memory has tended to consider memory as a superior and amodal process virtually independent from the perceptual characteristics of stimuli. Memory processes have been mainly studied using verbal and visual stimuli, as the presupposition has been that working memory is not a sensory store but is rather a superior stage of processing that is relatively autonomous from the sensory channels supporting signal acquisition (Baddeley, 2000). However, our results suggest that memory can be modulated by specific sensory features. In this context, future empirical and theoretical developments should consider the usefulness of a working memory model, which is composed of one subcomponent for each type of sensory memory, a resource managing system, and an episodic storage for integrated information; and the utility of a more general memory system affected by the idiosyncrasies of perceptual or other cognitive systems. The current working memory model cannot account for the results obtained by this study. Furthermore, a similar pattern of results would likely be found for smell and taste, which would confirm the existence of a modality-sensitive memory system.

This work has contributed to knowledge on the sensory specificity of memory and has suggested the need for a tactile or haptic storage component of working memory. Further investigation is required to confirm these pattern of results, with interference being presented in other phases of processing (retrieval and retention interval).

REFERENCES

Atinkson, R.C. & Schriffin, R.M. (1968). Human memory: A proposed system and its control processes. In K. W. Spence & J. T. Spence (Eds.), *The Psychology of Learning and Motivation: Advances in Research and Theory* (Vol. 2, pp. 89-195). New York: Academic Press

Baddeley, A.D. (1999). *Essentials of Human Memory.* UK: Taylor & Francis Psychology Press

Baddeley, A.D. (2000). The episodic buffer: a new component of working memory?. *Trends in cognitive sciences, 11*, 417-423

Baddeley, A.D. (2001). Is working memory still working?. *American Psychologist, 56*,849-864

Baddeley, A.D. (2003). Working memory: looking back and looking forward. *Nature reviews in neuroscience, 4*, 829-839

Baddeley, A.D., & Hitch, G. (1974). Working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory (*Vol. 8, pp. 47-89). New York: Academic Press.

Baddeley, A.D., Allen, R.J. & Hitch, G.J. (2010). Investigating the episodic buffer. *Psychologica Belgica, 50,* 223-243

Bushnell, E.W. & Baxt, C. (1999). Children's haptic and crossmodal recognition with familiar and unfamiliar objects. *Journal of Experimental Psychology: Human perception and performance, 25*, 1867-1881

Craddock, M. & Lawson, R. (2008). Repetition priming and the haptic recognition of familiar and unfamiliar objects. *Perception & Psychophysics, 70*, 1350-1365. doi: 10.3758/PP.70.7.1350

Gilson, E.Q., Baddeley, A.D. (1969). Tactile Short-Term Memory. *Quarterly Journal of Experimental Psychology 21*, 180-184

Donaldson, W. (1996). The role of decision processes in remembering and knowing. *Memory & Cognition*, 24 (4), 523-533.

Kaas, A.L., Stoeckel, M.C., Goebel, R. (2008). The Neural Bases of Haptic Working Memory. In: Grunwald, M. (Ed). *Human Haptic Perception: Basics and Applications*. Birkhuser Basel

Kiphart, M.J., Auday, B.C., & Cross, H.A. (1988). Short-term haptic memory for three-dimensional objects. *Perceptual and Motor Skills, 66*, 79-91

Kiphart, M.J., Hughes, J.L., Simmons, J.P., & Cross, H.A. (1992). Short-term haptic memory for complex objects. *Bulletin of the Psychonomic Society, 30*, 212-214

Klatzky, R.L. & Lederman, S.J. (1987). The representation of objects in memory: contrasting prespectives from vision and touch. In M. Gruneberg, P. Morris, R. Sykes (Eds.). *Pratical aspects of memory, vol. 2* (pp. 426-433). Chichester, G. B.: Wiley

Klatzky, R., Lederman, S.J., & Metzger, V. (1985). Identifying Objects by Touch - an Expert System. *Perception & Psychophysics*, *37*(4), 299–302.

Lacey, S. & Campbell, C. (2006). Mental representations in visual/haptic crossmodal memory: evidence from interference effects. *Quarterly Journal of Experimental Psychology, 59*, 361-76. doi:10.1080/17470210500173232

Lederman, S.J. & Klatzky, R.L. (1987). Hand movements: A window into haptic object recognition. *Cognitive Psychology, 19*, 342-368

Lederman, S.J. & Klatzky, R.L. (1990). Haptic classification of common objects: Knowledge-driven exploration. *Cognitive Psychology, 22*, 521-559

Lederman, S.J. & Klatzky, R.L. (2004). Haptic identification of common objects: Effects of constraining the manual exploration process. *Perception & Psychophysics, 66*, 618-628

Loomis, J.M., & Lederman, S.J. (1986). Tactual Perception. In K. Boff; L. Kaufman, & J. Thomas (eds): *Handbook of perception and human performance*. Wiley, New York, chapter 31.

Miles, C., Borthwick, M. (1996) Tactile Short-Term Memory Revisited. *Memory, 4,* 655-68

Millar, S. (1974). Tactile short-term memory by blind and sighted children. *British Journal of Psychology, 65*, pp. 253-263

Millar, S. (1999). Memory in touch. *Psicothema, 11*, pp. 747-767

Nabeta, T., & Kusumi, T. (2008). Memory capacity for haptic common objects [Abstract]. Abstract Supplement European Conference on Visual Perception, Perception, 37, p. 49

Neisser, U. (1967). *Cognitive Psychology*. New York: Appleton-Century Crofts.

Pureza, R. (2009). *Priming fonológico na recuperação de estados Tip-of-the-Tongue: O papel da posição e da extensão silábicas*. Unpubliched master´s thesis, University of Minho, Braga, Portugal

Shepard, R., & Metzler, J. (1971). Mental rotation of three dimensional objects. *Science, 171*, 701-3

Sperling, G. (1960). The information available in brief visual presentations. *Psychological monographs: general and applied, 74*, 1-29

Sullivan, E.V. & Turvey, M.T. (1972). On the short-term retention of serial, tactile stimuli. *Memory & Cognition, 2*, pp. 600-606

Recognising uncommon objects by touch in interference conditions[4]

ABSTRACT

This study intends to explore how haptic information is encoded in memory. Haptic recognition of uncommon objects is evaluated in five interference conditions at encoding: no interference, motor interference, haptic interference, verbal interference and visuospatial interference. Participants had to perform an haptic study phase simultaneously with an interference task, touching freely, with only one hand, and without vision, a set of 50 uncommon objects, presented sequentially for three seconds each. After this study phase, participants performed a surprise haptic recognition task within the "old/new" paradigm. Data shows that haptic, verbal and visuospatial interference conditions result in impairment in haptic recognition, while motor interference has no effect in haptic recognition. Moreover, haptic interference task performance reveals a trade-off effect when performed simultaneously with the haptic study phase, suggesting resource sharing among these tasks. This effect does not appear with the other interference tasks. These results point towards a haptic specificity in memory, and suggest that input modality plays a important role, not only at early perceptive stages of processing, but also in more complex tasks as recognition memory.

Research on haptics has proven that haptic recognition of everyday objects is both accurate and fast (Klatzky, Lederman, & Metzger, 1985). However, the diverse nature of haptic perception when exploring common and uncommon objects is well reported. For instance, the recognition of two-dimensional line drawings by touch is poor (Lederman, 1990), but identification of familiar objects is very good (Klatzky et al., 1985). Some studies have directly approached the differences between common and uncommon object perception by touch. Bushnell and Baxt (1990) in a crossmodal visuo-tactile study with adults and children, compare the performance in recognition tasks for familiar and unfamiliar objects in intramodal or crossmodal conditions (visuo-haptic and haptic-visual). Data in intramodal haptic conditions reveals that haptic recognition for unfamiliar objects is very high, and the authors consider this result as an evidence of efficacy of the sense of touch, since these objects could not have been encoded through a name tag, and had not been manipulated previously. However, more recent works have highlighted the relevance of verbal encoding in the recognition of uncommon stimuli. Lacey and Campbell (2006) in a study with familiar and unfamiliar objects in crossmodal visuo-haptic recognition, found verbal interference effects in haptic recognition, whether the interference was presented at encoding or at retrieval. Although the experiment did not include intramodal conditions, this result clearly shows that participants were tagging the stimuli with some type of verbal label, that is not necessarily a correct name or identification. Participants might be labelling items according to tactile

---

[4] Paper submitted to *Journal of Cognitive Psychology*

properties, like weight, temperature, shape or texture and using this verbal labels to help recognition (e.g., tagging an item as heavy, small, rough, or cold). In crossmodal visuo-haptic studies, the patterns of response have systematically revealed an advantage of crossmodal representations for familiar stimuli, in comparison with unfamiliar ones (Lacey, Flueckiger, Stilla, Lava, & Sathian, 2010; Deshpande, Hu, Lacey, Stilla, & Sathian, 2010).

Within touch, the pattern seems similar. Millar (1978) showed that stimuli grouping impaired nonsense shape recall, but facilitated braille letter recall by blind children. In previous works, Millar (1975a; 1975b) had shown that the nature of tactual serial memory was different from verbal serial memory. In these studies, participants were tested with objects (Millar 1975a) or with letters (Millar 1975b) that could be tactually similar, phonologically similar or dissimilar in both characteristics. Recall of stimuli lists was tested and showed that tactual similarity affected performance in lists up to five items, while phonological performance did not affect lists of two and three items.

Gilson and Baddeley (1969) presented a study with vibration stimuli applied to the participants' forearm. Results showed that in no interference conditions, tactual location recall accuracy increased in the first 10 seconds, presenting an asymptote at 60 seconds, while in verbal interference conditions (counting backwards in threes), recalled decreased progressively reaching an asymptote at 45 seconds. The authors suggest that memory for tactual stimuli may rely in two separate processes: a sensory register that is susceptible to distraction and a more durable process that is based on rehearsal, but not dependent on verbal cues. Miles and Borthwick (1996) revisited Gilson and Baddeley's (1969) study, and using the same procedure, got to different result patterns. In this study it seemed that tactile and articulatory suppression interferences acted in separate processes - there was a distinction between interval delay effects and articulatory suppression effects (Miles & Borthwick, 1996). Attending to these results, the authors assumed the existence of a sensory tactile memory that is not dependent on verbal rehearsal.

In 1974, Baddeley and Hitch's presented the working memory model. This model states that memory is a complex system, composed by a *central executive*, with attentional, decision, and managing functions, and two subcomponents, the *phonological loop*, mainly associated with the processing of verbal information, and the *visuospatial sketchpad*, responsible for visual and spatial encoding (Baddeley & Hitch, 1974). Later, Baddeley (2000) proposes the inclusion of the *episodic buffer*, a third subcomponent that would bind information processed in the other two subcomponents and integrate it with information held in long-term memory. The function of the episodic buffer was redefined in a more recent work (Baddeley, Allen & Hitch, 2010), in which this subcomponent is presented as a passive storage for information bound in the visuospatial sketchpad or the phonological loop.

One of the central features of this model is the assumption that perceived information is processed by a unique system, regardless of the sensory modality in which we perceive the stimuli. All information would have to be processed by this complex system, being encoded through verbal or visuospatial features, to be rehearsed and maintained in long-term memory. This perspective of memory as independent of sensory modalities, or as amodal, contrasts with the previous model presented by Atkinson and Schiffrin (1968) that assumed general sensory registers followed by a short-term store where information was rehearsed and encoded.

The relevance of modality specificity in memory has been suggested by other authors, even within the working memory model. Millar (1999) emphasises the role of movement in haptic memory and suggests the existence of a movement loop as a system of rehearsal for tactile information. More recently, the inclusion of a *tactual buffer* in the working memory model has been presented (Kaas, Stoeckel, & Goebel, 2008), considering neuropsychological findings that suggest specific neurological pathways for tactile stimuli, arguing in favour of touch-specific memories.

The nature of memory for touch needs to be further explored to understand how we process and remember stimuli perceived by touch and how we differentiate stimuli based on their tactile properties. Through a set of interference tasks, designed within the dual-task paradigm (e.g., Oberaurer & Göthe, 2006), this study will analyse the effects of interference at encoding in a haptic recognition task with uncommon objects. Considering that uncommon objects do not necessarily activate previous representations in long-term memory, they represent a type of stimuli that can be useful to explore the processes underlying tactile perception and cognition.

METHOD

Participants

Seventy-five participants (21 were male) took part in this experiment, with ages between 18 and 48 years old (*M* = 22.5, *SD* = 5.8). Participants were students and former students at University of Minho, and participated in the experiment for course credit (psychology students) or inclusion in a prize drawing for a gift card to an electronics store (former students and students from other graduations besides psychology).

Design

With this study we intended to evaluate the impact of various interference tasks at encoding in a haptic recognition task in the “old/new” paradigm.

Participants were divided in five groups, each corresponding to a different condition: no interference group, in which participants touched the objects in the study phase and then performed an immediate haptic recognition task; and four interference condition groups, in which participants initially touched the objects while performing an interference task, and then performed the haptic recognition task. The interference task could be motor, haptic, verbal or visuospatial. The participants were randomly distributed through the five conditions, with 15 participants in each condition.

Participants in haptic, verbal and visuospatial interference conditions performed the interference task twice in such a way that we were able to establish a baseline performance in each of the interference tasks (haptic, verbal and visuospatial), that we could later compare with performance when the participants were simultaneously touching the haptic stimuli. Motor interference only required doing a sequence of movements with the dominant hand, and did not imply an answer to a question, and as such its performance cannot be evaluated and is not included in the interference task performance analysis.

Participants never saw the objects during the experiment and they did not know that there would be a haptic recognition task after the haptic study phase. The experiment was presented as an exploratory study, evaluating how people performed in dual task conditions. It was not mentioned that the experiment implied a memory task or that there would be a test on the studied objects. The no interference task was presented as a training phase for a subsequent task, and no other information was provided at the beginning of the experiment.

Materials and Stimuli

The experimental set-up is composed by a wooden box (with two openings, one facing the participant, covered by a cloth to prevent visual contact with the stimuli and another facing the experimenter) divided by a cardboard in the interior. The box was placed on a table, and had a 17'' computer screen on top of it. The computer screen was used to present verbal and visuospatial stimuli in the interference tasks. During the whole experiment, the participants had to wear headphones and heard a continuous white noise sound to mask any manipulation sounds from the objects.

The stimuli set is described in Appendix A and was composed by 83 everyday uncommon objects (e.g., *plastic onion*, *miniaturised bucket*, unconventional design *flash drive*) that were previously evaluated regarding familiarity, in a five point Likert scale, in which *one* was defined as “an object that you never use or use less than once a year” and *five* was defined as “an object that you use everyday or almost everyday (*M* = 2.5, *SD* = 0.6); and identification (*M* = .37, *SD* = 0.3). These data can be consulted in Appendices E (familiarity data) and F (identification data). The criteria to select the objects was that they were small enough to be explored with one hand, and that allowed silent manipulation.

For the haptic interference task, the stimuli were composed by pairs of paper samples that the participant had to compare, evaluating if each pair was the same (two samples from the same type of paper) or different (each of the samples came from a different type of paper). Previous studies (described in Appendix C), concerning the evaluation of similarity between each of the created pairs, showed that the participants were able to correctly differentiate the “different” paper sample pairs. In a 10 point likert scale (in which *one* was defined as “completely different samples”, and *ten* was defined as “the samples are the same”), “same” pairs presented a similarity evaluation of 8.7 (*SD* = 1.8) and “different” pairs an average of 5.2 (*SD* = 3.2).

In verbal interference, participants had to evaluate pseudo-word pairs that were presented in the computer screen. The stimuli were trisyllable pseudowords selected from Pureza (2009). “Same” pairs were composed by the same pseudo-word presented twice, with randomised syllable order (e.g. TA - FA - LE / FA - LE - TA), while “different” pairs were composed by swapping either a vowel or a consonant between syllables in the pseudo-word and presenting the syllables in a randomised order (e.g. NO - SI - NE / NI - NE - SO). Preliminary studies to define the stimuli set are described in Appendix D.

Visuospatial interference stimuli were selected from (Shepard & Metzler, 1971) stimuli. “Same” pairs were composed by two representations of the same objects with a 40º rotation between them. “Different” pairs were representations of one object and its mirror image with a 40º rotation. Previous studies allowed us to define the 40º rotation as the maximum rotation participants could resolve (performance above chance, maintaining task difficulty) in three-seconds presentations and in dual task conditions (see Appendix B).

Procedure

Participants sat in an adjustable stool in front of the table and placed both hands inside the wooden box, one in each side of the cardboard.

In no interference, verbal and visuospatial interference conditions, participants were asked to placed their non-dominant hand in the bottom of the box, with the palm facing up. The dominant hand was placed on the bottom of the box as well, but in a comfortable resting position. For motor and haptic interference conditions, the dominant hand was positioned at the box ceiling, with the palm facing down. This way, participants were able to quickly start performing the movements required in these tasks.

For the haptic study phase, as well as for the haptic recognition tasks, the object was directly placed in the participant’s non-dominant hand by the experimenter.

The haptic interference task consisted in the evaluation of paper samples. Participants had to rub the paper sample pairs with their fingers and evaluate if the two presented samples came from the same or different types of paper, providing an answer to the question: “Are the two samples equal?”. This task was synchronised with the haptic study phase, and as such participants started to explore simultaneously the object with the non-dominant hand and the paper samples with their dominant hand.

Motor interference procedure was exactly the same as haptic interference procedure, but the participants did not evaluate any paper samples, they simply rubbed the bottom of the wooden box in every trial, and did not have to provide any answer to the interference task.

Verbal and visuospatial interference task stimuli were presented in the screen in front of the participants. In verbal interference participants were required to read out loud the pseudo-words, and then to provide an answer to the question: “Do the two pseudo-words have exactly the same syllables?”. The visuospatial task implied that participants mentally rotated the presented three-dimensional figures, to answer to the following question: “Are the two figures representations of the same objects in different rotations?”.

In every task, the stimuli presentation was of three seconds and was synchronised with the presentation of the haptic stimuli: for each presented object the participants were simultaneously and according to the condition, evaluating a paper pair with the dominant hand, performing a specific movement with the dominant hand and arm, reading a pseudo-word pair, or evaluating the three-dimensional stimuli pairs regarding rotation.

Haptic recognition was presented immediately after haptic study phase. In this task, participants touched each object for three seconds with their non-dominant hand and were instructed to provide an answer as quickly and accurate as possible. Participants touched 50 objects, 25 old (presented objects) and 25 new (non-presented objects) and they were asked to report, for each touched object if it was an old or new item.

RESULTS

Overall, the participant's presented recognition rates better than chance (.50) in no interference, *t* (14) = 18.0, *p* < .001, motor interference, *t* (14) = 11.2, *p* < .001, haptic interference, *t* (14) = 6.5, *p* < .001, verbal interference, *t* (14) = 5.0, *p* < .001, and visuospatial interference, *t* (14) = 7.9, *p* < .001. This result reveals that it is possible to successfully recognise uncommon stimuli by touch only, after a three seconds haptic exploration. Data from haptic recognition is represented in Figure 2, according to interference condition.

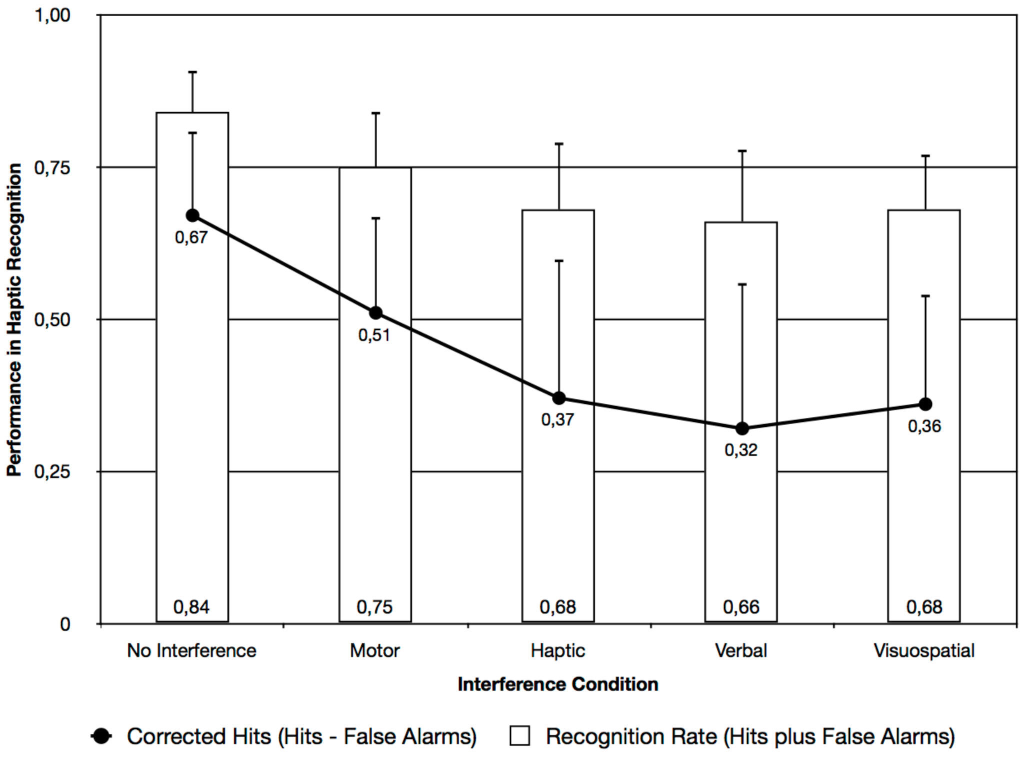

Figure 2: Recognition rates (hits plus correct rejections) and corrected hits (hits minus false alarms) for haptic recognition of uncommon objects according to interference condition

The corrected hit rates (hits minus false alarms) were taken as an accuracy measure and analysed through a one-way ANOVA test. The results from the test show a significant effect of interference in haptic recognition, *F* (4, 34.7) = 10.2, *p* < .001, *r* = .565. Post-hoc Games-Howell test showed that motor interference is no different from no interference (*p* = .063), while haptic (*p* = .002), verbal (*p* = .001) and visuospatial (*p* < . 001) interference originated significantly different recognition rates compared to the no interference condition. These data show that a simultaneous demanding interference task at encoding results in an impairment of haptic recognition for uncommon objects. There are no differences between haptic recognition rates in all other combinations (*p* > .05).

The values of B''_D Donaldson (1996) are equivalent in all conditions, *F* (4, 74) = 1.20, *p* = .321, *r* = .252, revealing that there are no criteria shifts in the haptic recognition task. In no interference conditions B''_D has a mean value of .10 (*SD* = .40), motor interference condition of .15 (*SD* = .46), haptic interference has a mean value of .33 (*SD* = .38), verbal interference of .28 (*SD* = .36) and visuospatial interference of .08 (*SD* = .34).

Taking a look into performance in interference tasks, it is possible to understand whether the haptic study phase had any effect in the concurrent task, and evaluate the existence of any trade-off effects, with one task affecting the other. Only haptic, verbal, and visuospatial interference will be considered, since the motor interference task did not require a response, and as such cannot be evaluated.

Table 2 shows the average corrected hits values for each task in each interference condition. It is possible to observe that the haptic task presents the lowest accuracy rates either in single or dual task conditions. A repeated measures ANOVA, attending to within subjects manipulation of task condition (single or dual task performance), and between subjects manipulation of interference type (haptic, verbal or visuospatial), shows that task condition does not affect performance, *F* (1, 42) = 0.39, *p* = .535, *r* = .300. Indicating that participants were performing at about the same level in single or dual task conditions. The nature of the interference tasks presents a significant effect, *F* (2, 42) = 7.37, *p* = .002, *r* = .510. Post hoc Games-Howell test showed that haptic interference resulted in significantly different results from verbal interference (*p* < .001) but not from visuospatial interference (*p* = .276). Verbal and visuospatial interference do not differ from each other (*p* = .175). There are no interaction effects between task condition and type of interference, *F* (2, 42) = 0.72, *p* = .491, *r* = .181.

When we directly compare the t-test for each one of the three interference tasks, performed in single and dual conditions (and applying the Bonferroni correction, α/3 = .017), we can observe that only haptic interference presents an impaired performance in dual task, *t* (14) = 2.77, *p* = .015, *r* = .595, while verbal interference, *t* (14) = −0.39, *p* = .702, *r* = .104, and visuospatial interference, *t* (14) = 0.15, *p* = .883, *r* = .040, present equivalent performances in single and dual task.

These results reveal that only haptic interference presents a tradeoff effect when it is performed simultaneously with a haptic encoding task. Participants in the haptic interference group, not only showed an effect of haptic interference in haptic recognition, showing lower recognition rates than the group in no interference condition; but also revealed an effect of object manipulation in the paper evaluation task, revealing that the haptic task impaired performance in paper discrimination.

Table 2: Corrected hits values for haptic, verbal, and visuospatial interference tasks in single- and dual-task conditions for uncommon objects (standard deviations are presented between brackets)

	Haptic Interference Task	Verbal Interference Task	Visuospatial Interference Task
Single-task condition	.54 (.10)	.72 (.14)	.58 (.33)
Dual-task condition	.46 (.13)	.75 (.22)	.61 (.24)

DISCUSSION

This study shows that haptic recognition performance with uncommon three-dimensional objects presented recognition rates greater than chance even in interference conditions. Moreover, considering the interference results, that the stimuli set was composed by uncommon objects, and attending to prior research (Bushnell & Baxt, 1990), we can argue that haptic recognition was not only a consequence of prior verbal or visuospatial representations of the objects, but resulted from the haptic processing that took place during the experiment.

The presentation of a demanding interference task at encoding resulted in haptic recognition impairment in haptic, verbal and visuospatial interference conditions, but not in motor interference, suggesting that participants might be using haptic, verbal and visuospatial cues at encoding, while motor cues are not determinant for performance.

Previous literature reports that using uncommon or unfamiliar objects results in more difficult memory and identification tasks than common or familiar stimuli (e.g. Bushnell & Baxt; Lacey & Campbell, 2006). With familiar stimuli, we can mobilise a larger set of resources, since the binding between visual, verbal, haptic, olfactive, semantic and affective cues of the stimuli are very strong, and the activation of one of these cues might be sufficient to enable all the other representations. With uncommon objects, on the other hand, the type of cues we can access are frequently restricted to the ones we can extract from the stimuli at presentation time, and other complex associations we might intentionally form to better recall the items. This type of processing is slower and more demanding, implying an active effort to associate items and to identify them as a whole, not as an amalgam of features, but integrating different properties.

Lederman and Klatzky (1990) showed that object manipulation is driven by previous knowledge about the objects, and that rather abstract categorical information about an object can significantly increase its identification rates (Klatzky & Lederman, 1995), for instance, mentioning the cue “writing utensil” fastens the haptic identification of “pencil”. Considering these aspects, uncommon object recognition presents a disadvantage, since previous knowledge about each specific item is not established and as such, any attempt to intentionally look for specific features would not be successful.

Considering that haptic recognition of uncommon objects is a resource demanding task, and that participants could only identify the objects in about 37% of the trials (Appendix F), we can assume that participants were trying to use every available resource to tag the items. According to the participants is this study, the urge to identify the objects was automatic, although they were not asked to do it. In that effort, some participants reported trying to tag the object, giving them names that they knew did not correspond to the true object (e.g. one participant reported tagging the miniaturised clay hat as a “heavy bell”), or imagining how the stimuli would look like and trying to visualise a scene with the object in it. These types of strategies might be enough to explain the effects of verbal and visuospatial interference in haptic recognition, since these tasks would definitely impair verbal or visual rehearsal.

Another main finding of this study concerns a trade-off effect in haptic interference conditions. Not only haptic interference affected haptic recognition, but the execution of these two simultaneous tasks led to an impaired performance in the haptic paper evaluation which presents worst performance in dual than in single task conditions. This finding is interesting as it suggests resource sharing between the two tasks. The significance of these data is better understood if we considered that motor interference did not impair haptic recognition. As such, haptic interference does not result from an increased task difficulty resulting from doing independent tasks with the two hands, but seems to be directly related to the cognitive nature of the haptic task. According to these data we might assume a tactile specificity in working memory. Moreover, haptic interference was the task that resulted in larger impairment of haptic recognition, even though both verbal and visuospatial tasks affected haptic recognition as well. We believe that this resource sharing between the two haptic tasks might have been responsible for the differences between the verbal interference and the haptic interference task performance. Both task have been used in previous experiments (Fernandes & Albuquerque, submitted), and revealed no differences in performance.

Baddeley and Hitch’s (1974; Baddeley, 2000) working memory model, assumes that, regardless of the input modality, stimuli information is processed in one of two ways in working memory: either verbal or visuospatial. In this case, any name tag assumed by the participants is a verbal label that would imply the intervention of the phonological loop, while any attempt to visualise the stimuli, or spatially manipulate them would result in processing by the visuospatial sketchpad. These two storages can communicate among themselves through the episodic buffer, that also integrates the upcoming information from the environment with long-term representations. In this model, there is no space for modality-specificity, and information acquired by touch, taste or smell would have to be translated in verbal or visuospatial codes to be maintained in memory. However, in the present study, we can observe that even with a simultaneous verbal or visuospatial interference task at encoding, participants were able to haptically recognise the objects with performance greater than chance. Simultaneously, it was the haptic interference task that resulted in the greater impairment of haptic recognition.

Concluding, the present data suggests modality specificity in cognition. The perceptual modality through which we perceive information might be crucial to the way we process and integrate information about the stimuli. Baddeley and Hitch's (1974) working memory model, introduced the idea that cognitive processing was amodal and implied the recoding of information perceived through touch, smell and taste, but not of the visual and auditive modalities, that present a clear implicit connection with the visuospatial sketchpad and the phonological loop. Most research in the working memory has in fact been conducted with visual, spatial and verbal stimuli (Baddeley, 2001; Repovs & Baddeley, 2006), even though research regarding other sensory modalities has shown some modality specificity in cognition (Auvray & Spence, 2008; Gottfried, Smith, Rugg, & Dolan, 2004; Larsson & Backman, 1998). We argue that cognitive research, specifically research on memory, can no longer disregard the data obtained from studies with touch, taste and olfaction, specially when research in these area is coherently pointing to a modality dependent cognition.

REFERENCES

Atkinson, R., & Shiffrin, R. (1968). Human memory: A proposed system and its control processes. In K. Spence (Ed.), *The psychology of learning and motivation: advances in research and theory* (Vol. 2, pp. 89–195). New York: Academic press.

Auvray, M., & Spence, C. (2008). The multisensory perception of flavor. *Conscious Cognition*, *17*(3), 1016–1031. doi: 10.1016/j.concog.2007.06.005

Baddeley, A.D. (2000). The episodic buffer: a new component of working memory *Trends in Cognitive Sciences*, *4*(11), 417–423. doi:10.1016/S1364-6613(00)01538-2

Baddeley, A.D. (2001). Is working memory still working. *American Psychologist*, *56*(11), 851–864. doi: 10.1037/0003-066X.56.11.851

Baddeley, A.D., & Hitch, G.J. (1974). Working Memory. In G. Bower (Ed.), *The psychology of learning and motivation* (pp. 47–89). New York: Academic Press.

Baddeley, A.D., Allen, R., & Hitch, G.J. (2011). Binding in visual working memory: The role of the episodic buffer. *Neuropsychologia*. doi:10.1016/j.neuropsychologia.2010.12.042

Bushnell, E.W., & Baxt, C. (1990). Children's Haptic and Cross-Modal Recognition With Familiar and Unfamiliar Objects. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(6), 1867–1881.

Deshpande, G., Hu, X., Lacey, S., Stilla, R., & Sathian, K. (2010). Object familiarity modulates effective connectivity during haptic shape perception. *NeuroImage*, *49*(3), 1991–2000. Elsevier B.V. doi:10.1016/j.neuroimage.2009.08.052

Donaldson, W. (1996). The role of decision processes in remembering and knowing. *Memory & Cognition*, 24 (4), 523-533.

Fernandes, A.M. & Albuquerque, P.B. (submitted). Haptic recognition of common objects: The effects of interference at encoding.

Gilson, E.Q., & Baddeley, A.D. (1969). Tactile short-term memory. *Quarterly Journal of Experimental Psychology*, *21*(2), 180–184.

Gottfried, J., Smith, A., Rugg, M., & Dolan, R. (2004). Remembrance of Odors Past: Human Olfactory Cortex in Cross-Modal Recognition Memory. *Neuron*, *42*(4), 687–695. doi:10.1016/S0896-6273(04)00270-3

Kaas, A., Stoeckel, M., & Goebel, R. (2008). The neural bases of haptic working memory. In M. Grunwald (Ed.), *Human haptic perception: Basics and applications* (pp. 113–129). Basel: Birkhäuser.

Klatzky, R.L., & Lederman, S.J. (1995). Identifying objects from a haptic glance. *Percept Psychophys*, *57*(8), 1111–1123.

Klatzky, R.L., Lederman, S.J., & Metzger, V. (1985). Identifying Objects by Touch - an Expert System. *Perception & Psychophysics*, *37*(4), 299–302.

Lacey, S., & Campbell, C. (2006). Mental representation in visual/haptic crossmodal memory: evidence from interference effects. *Quarterly Journal of Experimental Psychology*, *59*(2), 361–376. doi:10.1080/17470210500173232

Lacey, S., Flueckiger, P., Stilla, R., Lava, M., & Sathian, K. (2010). Object familiarity modulates the relationship between visual object imagery and haptic shape perception. *NeuroImage*, *49*(3), 1977–1990. doi:10.1016/j.neuroimage.2009.10.081

Larsson, M., & Backman, L. (1998). Modality memory across the adult life span: Evidence for selective age-related olfactory deficits. *Experimental Aging Research*, *24*(1), 63–82.

Lederman, S.J. & Klatzky, R.L.. (1990). Haptic Classification of Common Objects: Knowledge-Driven Exploration. *Cognitive Psychology*, 22, 421-459.

Miles, C., & Borthwick, M. (1996). Tactile short-term memory revisited *Memory*, *4*(6), 655–668.

Millar, S. (1999). Memory in touch. *Psicothema*, 11(4), 747-767.

Millar, S. (1975a). Effects of phonological and tactual similarity on serial object recall by blind and sighted children. *Cortex, 11(2), 170-180.*

Millar, S. (1975b). Effects of tactual an phonological similarity on the recall of braille letters by blind children. *British Journal of Psychology*, *66*(2), 193–201. doi:10.1111/j.2044-8295.1975.tb01455.x

Millar, S. (1978). Short-term serial tactual recall: Effects of grouping on tactually probed recall of Braille letters and nonsense shapes by blind children. *British Journal of Psychology*, *69*(1), 17–24. doi:10.1111/j.2044-8295.1978.tb01628.x

Oberauer, K., & Göthe, K. (2006). Dual-task effects in working memory: Interference between two processing tasks, between two memory demands, and between storage and processing. *European Journal of Cognitive Psychology*, *18*(4), 493–519. doi:10.1080/09541440500423038

Pureza, R. (2009). *Priming fonológico na recuperação de estados Tip-of-the-Tongue: O papel da posição e da extensão silábicas*. Unpublished Master´s thesis, University of Minho, Braga, Portugal

Repovs, G., & Baddeley, A.D. (2006). The multi-component model of working memory: Explorations in experimental cognitive psychology. *Neuroscience*, *139*(1), 5–21. doi:10.1016/j.neuroscience.2005.12.061

Shepard, R.N., & Metzler, J. (1971). Mental Rotation of Three-Dimensional Objects. *Science*, *171*(3972), 701–703. doi: 10.1126/science.171.3972.701

Interference effects in haptic recognition of common and uncommon objects

ABSTRACT

The effect of motor, haptic, verbal, and visuospatial interference at encoding in a haptic recognition tasks is compared to performance in no interference conditions for common and uncommon objects. Participants had to touch, without sight, 50 objects for three seconds each with their non-dominant hand. Simultaneously, during the haptic study phase, participants had to perform an interference task that required a yes / no answer in each trial. An immediate incidental haptic recognition task was presented at the end, in which participants had to differentiate presented from non presented items in a set of 50 objects. Results show that common object recognition is always superior to uncommon object recognition. Haptic interference affected performance for both object types. Uncommon, but not common objects, show an interference effect from verbal and visuospatial interference. Results are discussed attending to the nature of common and uncommon object representations, and also to working memory models.

Everyday we use the sense of touch to perform simple tasks: we are able to select the correct key from our keychain while it is in our pocket, and we can choose the right coin in our wallet while looking at the store seller. These tasks appear to be simple and immediate and seem to require no effort at all. However, experimental studies on haptic perception with schematic, less complex objects, reveal that we perform badly when using only the sense of touch. For instance, raised line drawings are very difficult to identify by touch (Wijntjes, van Lienen, Verstijnen, & Kappers, 2008), and abstract 3D objects are difficult to match by touch only (Norman, Norman, Clayton, Lianekhammy, & Zielke, 2004). Other studies also reveal that object familiarity seems crucial to performance in recognition tasks (Deshpande, Hu, Lacey, Stilla, & Sathian, 2010; Lacey, Flueckiger, Stilla, Lava, & Sathian, 2010). What is it then, that makes the difference between good and bad performance in the sense of touch? Are we using specific tactile cues in experimental studies when facing odd objects, while we use mainly verbal or visuospatial cues in everyday tasks with common objects? In this paper we intend to explore haptic memory, comparing the impact of motor, haptic, verbal and visuospatial interference tasks in haptic recognition for common and uncommon three-dimensional everyday objects.

Processes underlying tactile cognition are still not sufficiently explored. As Cattaneo & Vecchi (2011) pointed out, the “tyranny of the visual” (p. 3) has led research in human cognition and left the other sensory modalities behind. Even when analyzing touch experiments, the most common approach has been comparing visual and tactile performance within crossmodal paradigms (e.g. Bushnell & Baxt, 1990; Haag, 2011; Lacey & Campbell, 2006; Paz, Mayas, & Ballesteros 2007). The fact that spatial encoding presents a central role both in vision and in touch (Millar, 1999), as well as the fact that both sensory modalities allow evaluation of properties such as size, shape or texture, has led researchers to hypothesise that identical processes rule both sensory modalities (Easton & Srinivas, 1997). Although a strong bind exists between visual and tactual representations, experiments with both modalities do not show a congruent set of results, implying that there is modality specificity in perception and cognition (Klatzky & Lederman, 1987) and suggesting that although vision and touch share spatial representations, they also might present distinct processes for specific visual and tactual features.

Likewise, the relevance of verbal cues in our everyday experience is important. Specially when we are talking about everyday objects, we cannot disregard the automatic name tagging that occurs when we touch a stimulus. This name-tag does not necessarily need to be a correct object identification. Participants can use verbal labels for specific tactile properties that allow stimuli discrimination, such as reporting to a specific stimulus as “cold” or to another one as “the heaviest”. Previous studies (Lacey & Campbell, 2006) have shown that unfamiliar objects’ haptic recognition is affected by verbal interference, confirming the hypothesis that some kind of verbal information is being used to encode and retrieve information about the stimuli.

The hypothesis that tactile information can be processed through visuospatial or verbal codes has to be considered in relation to the working memory model (Baddeley & Hitch, 1974; Baddeley, 2000). This model argues that working memory is a complex system that can be divided in one component, the *central executive*, and three subcomponents, the *phonological loop*, the *visuospatial sketchpad*, and the *episodic buffer*, all interconnected (Baddeley & Hitch, 1974; Baddeley 2000; Baddeley, Allen, & Hitch, 2010). In this model, the phonological loop is described as a verbal and auditory storage and the visuospatial sketchpad is associated with the manipulation of visual and spatial information. As such, it is easy to assume an almost linear connection between audition and the phonological loop and between vision and the visuospatial sketchpad, although Baddeley (1999) has argued that working memory is a higher level system that has no direct connection with perceptual input. In this context, and considering that there is no specific component with a relation to touch, taste or smell, one must presume that information perceived through these sensory modalities, needs to be encoded as a verbal or visuospatial code, since information has to be processed in at least one of these subcomponents. Studies about memory for touch, taste and smell are scarce. Regarding memory for touch, experiments usually do not address memory for specific tactile features (like temperature, weight or relief), and present stimuli with verbal (e.g. Bliss, Kujala & Hämäläinen, 2004) or visual (Loomis, Klarzky, & Lederman, 1991) nature, forcing verbal or visuospatial encoding, and not clarifying the existence of specific tactile processing (Kaas, Stoeckel, & Goebel, 2008).

In this study we conducted an analysis of haptic memory, comparing common and uncommon objects. The option for everyday, three-dimensional complex objects was made considering the reported divergent results of haptic experiments with abstract and concrete stimuli (Klatzky, Lederman, & Metzger, 1985). We intended to evaluate haptic memory capacity and accuracy in optimal conditions for this modality, allowing for free exploration and presenting complex objects.

With identifiable objects, the relevance of naming and mental images is particularly salient, since participants might use only these type of cues when trying to recognise the stimuli. Familiarity has also been proven to affect performance in memory tasks with haptic stimuli (Bushnell & Baxt, 1990; Craddock & Lawson, 2008). Performance with familiar objects tends to be better than with unfamiliar objects and memory for common objects seems to be more sensible to prior knowledge about the stimuli, allowing faster identification when the item is presented in a canonical orientation (Craddock & Lawson, 2008) or with size congruency (Craddock & Lawson, 2009). Some authors have argued that familiar objects present more robust cognitive representations that allow a faster and accurate processing (Lacey & Campbell, 2006) in comparison with unfamiliar objects, that demand more processing resources. However, previous studies have shown that verbal cues might be particularly helpful in the processing of unfamiliar objects (Lacey & Campbell, 2006). Due to the strong representation of familiar objects in long-term memory, the perception of one feature might activate a whole network of multimodal representations, making the stimuli very resistant to interference; on the other hand, to encode uncommon objects, participants would need to create new representations of these objects and link them to the perceived features (Bushnell & Baxt, 1990; Lacey & Campbell, 2006). This process requires more cognitive resources and active manipulation of the stimuli, and as such can be more susceptible to interference by other tasks.

In a working memory framework, a more demanding task will imply a worst performance than a less demanding one (e.g. Oberauer & Göthe, 2006). As such, we would expect performance for uncommon objects to be worst than for common objects, regardless of task condition. Furthermore, in a dual task paradigm, an interference task should affect uncommon objects in a greater extent than common objects, since the resources demand increases in dual task and the more difficult tasks tend to be more affected by resource sharing (e.g. Anderson, Reder, & Lebiere, 1996). Concerning the memory systems for touch, if there is a haptic-specifity in working memory, we would expect similar interference patterns for information perceived by touch, regardless of object familiarity. During this paper, to simplify language we will use the terms common and familiar as synonymous, as well as uncommon and unfamiliar.

METHOD

The following results are a reanalysis of the data presented in the two previous studies (Fernandes & Albuquerque, *submitted a; Fernandes & Albuquerque, submitted b).* To directly compare the impact of each interference type regarding common and uncommon objects we restructured the previous data in five experiments, directly comparing the results for each interference type (motor, haptic, verbal, and visuospatial) with the results in no interference conditions. Experiment 1 will report the data for no interference conditions only, Experiment 2 explores the effect of motor and haptic interference, Experiment 3 analyses data for verbal interference, and finally Experiment 4 report to visuospatial interference data. Since these analysis are conducted on data previously presented, we will only report the results with the new approach to the data, omitting the method information, and then we will present a brief discussion within each experiment, ending with a general discussion of the comparison of uncommon and common objects in all five conditions.

EXPERIMENT 1: Haptic recognition of common and uncommon objects[5]

RESULTS

Haptic recognition presents values above chance for common (.92 of correct answers, *SD* = .01) and uncommon objects (.84 of correct answers, *SD* = .02).

Figure 3 represents the values of corrected hits (hits minus false alarms) for haptic recognition that are taken as an accuracy measure. Haptic recognition of common objects is clearly superior to haptic recognition of uncommon objects, and this is confirmed by the t-test results, *t* (21.9) = 4.3, *p* < .001, *r* = .677.

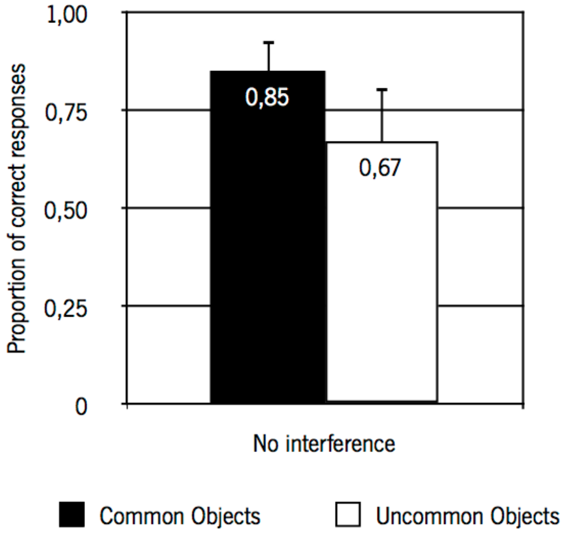

Figure 3: Corrected hits in haptic recognition with no interference according to object type

The values of B''$_D$ (Donaldson, 1996) reveal that participants had similar criteria in both conditions, *t* (28) = .71, *p* = .48, r = .133.

DISCUSSION

Previous findings had established that touch is an accurate a fast modality (Klatzky et al., 1985). With these data we can confirm that haptic recognition is highly effective either with common or uncommon objects,

---

[5] Method for this experiment is described in the first and second articles in this thesis. Further information on the stimuli can be found in Appendices A, E, and F.

and even when participants are not aware that they will be tested on the studied objects (incidental recognition task).

Common object's recognition was found to be better than uncommon object's recognition. This result is also documented in previous research (Bushnell & Baxt, 1990; Lacey & Campbell, 2006) and is congruent with our hypothesis. This result can be read in two different ways: as an implication of different processes underlying common and uncommon objects' representations, or as a result of increased task difficulty in the uncommon objects condition. These two perspectives can also be conciliated, as we will see along this discussion.

Some authors have argued that the representations of common and uncommon objects are different. Johnson, Paivio and Clark (1989) propose that while both familiar and unfamiliar objects have a visual representation, familiar objects also present a verbal representation that is not available for unfamiliar stimuli. As such, a visual encoding strategy would be adopted for unfamiliar objects, while either visual or verbal strategies could be implemented with familiar stimuli. This would justify why common objects systematically show better recognition rates than uncommon objects, a result that was confirmed in this experiment.

Within working memory paradigms, task difficulty is directly associated with an increase in cognitive demands to perform the task (e.g. Anderson et al. 1996). The working memory model (Baddeley & Hitch, 1974; Baddeley, 2000) states that the central executive is responsible for attentional control, resource managing and decisional processes. As such, this component should distribute attention and other resources in the subcomponents (phonological loop and visuospatial sketchpad). A consequence of this hypothesis is that every time we have an overload of resources in one of the subcomponents, the central executive would not be able to maintain performance level, and the subject would not be able to correctly perform a task (e.g. Conway & Engle, 1994). In the present study, haptic recognition of uncommon objects revealed worst results than common object recognition, implying that more resources were mobilised during the uncommon haptic recognition task. One possibility is that participants were not able to apply a systematic and efficient strategy at encoding, resulting in an overload of working memory.

As mentioned before, these two perspectives are easily integrated, assuming that what increases task difficulty is the need to mobilise more resources to process the uncommon objects, in comparison with common objects. For common objects, binding processes between haptic, verbal and visuospatial cues can be automatic, facilitating stimuli encoding and activating large networks of multisensory information and previous knowledge about the stimuli. For instance, when we touch a pencil we immediately identify it, and generate a mental image of it, knowing its function and probably handling it accordingly. On the contrary, uncommon objects do not elicit automatic integration of different cues. When we touch an uncommon object we can try to create a mental image of the object, but for this image to be stable we need to deeply explore the object and it is relevant to notice that tactile processing is sequential and not parallel, which demands a longer exploration. Also, uncommon objects are not immediately associated with a name, so we can use a verbal label, but we have to choose a salient feature from the object to tag it, for instance, its temperature, and intentionally associate this tactile information with its verbal tag (for instance, is this the colder object or just a cold one?).

EXPERIMENT 2: The Effect of Motor and Haptic Interference[6]

RESULTS

Data from Experiment 1 will be considered as a control condition in this experiment.

A 2x3 ANOVA was conducted analysing the effects of object type (common or uncommon) and haptic study condition (no interference, motor interference or haptic interference) regarding corrected hits values in haptic recognition. Results are presented in Figure 1. Both object type, *F* (1, 84) = 40.52, *p* < .001, *r* = .570 and interference condition, *F* (2, 84) = 33.37, *p* < .001, *r* = .666, reveal significant effects in haptic recognition. Common objects present higher recognition rates than uncommon objects and Bonferroni post-hoc tests show that no interference and motor interference conditions are similar (*p* = .164) and that haptic interference is significantly different from no interference (*p* < .001) and motor interference (*p* < .001). There was an interaction effect between the variables, *F* (2, 84) = 3.61, *p* = .031, *r* = .281, revealing that uncommon objects were more affected by interference than common objects.

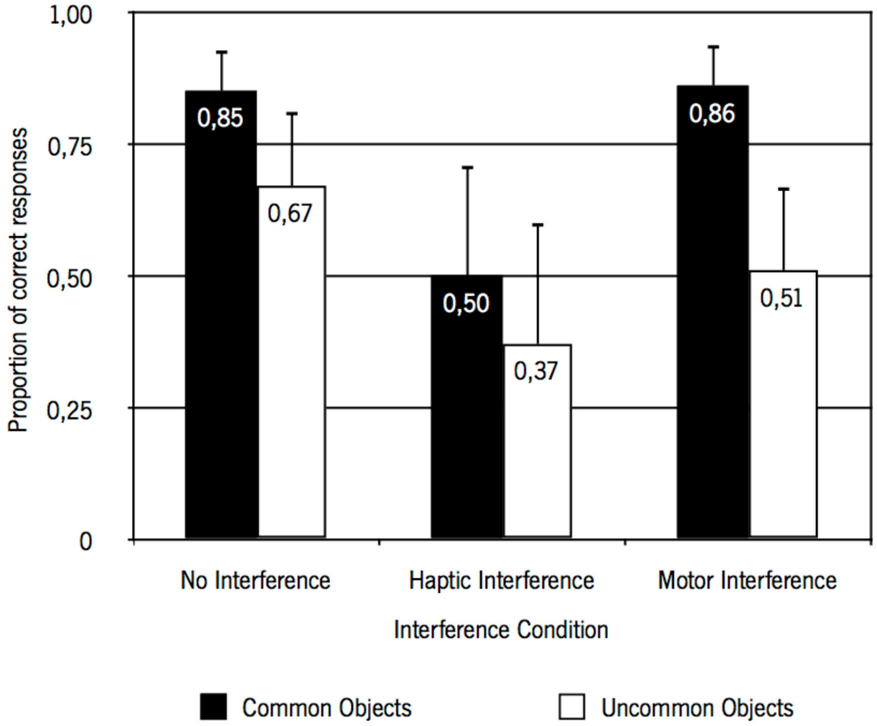

Figure 4: Corrected hits in haptic recognition with no interference, motor, and haptic interference according to object type

---

[6] Method for this experiment is described in the first and second articles in this thesis. Further information on the stimuli can be found in Appendices A, E, and F.

B''D values (Donaldson, 1996) result in similar criteria regarding object type, *F* (1, 84) = .15, *p* = .70, *r* = .045, interference task, *F* (2, 84) = 1.68, *p* = .19, *r* = .197, and no interaction effect was found between variables, *F* (2, 84) = .65, *p* = .52, *r* = .122. These values show that participants were able to maintain their criteria stable in the haptic recognition task, regardless of experimental condition.

Performance in the haptic interference task is also relevant for the present study, as it allows us to evaluate possible tradeoff effects between the paper evaluation task and haptic study phase. A 2x2 repeated measures ANOVA was conducted attending to object type (common or uncommon) and to interference task condition (performed by itself or simultaneously with haptic study). Statistical data show that performance is equivalent regardless of the type of objects, *F* (1, 28) = .758, *p* =.391, *r* = .161, or interference task performance condition, *F* (1, 28) = 1.056, *p* = .313, *r* = .190. Also, no interaction was found, *F* (1, 28) = 3.808, *p* = .061, *r* = .346. These results (shown in table 3) confirm that, as intended, participants were focused on the haptic interference task, regardless of the task they were performing, and that the simultaneous haptic study phase did not affect performance in the haptic interference task. These results can assure that any impairment in haptic recognition is due to the presence of the haptic interference task and not due to any interaction between the tasks performed by both hands.

Table 3: Corrected hits for haptic interference according to task condition and object type (standard deviations are presented between brackets)

	Haptic Interference Single-Task	**Haptic Interference Dual-Task**
Common Objects	.51 (.12)	.54 (.10)
Uncommon Objects	.54 (.10)	.46 (.13)

DISCUSSION

Common and uncommon object's haptic memory revealed a similar pattern across conditions. Although common objects' memory is systematically better than uncommon objects' memory, both were affected by a haptic interference task at encoding, and none was impaired by a motor interference task.

The role of movement in haptics is well documented. Since the early experiments on touch, authors have highlighted the relevance of movement in the recognition and identification of stimuli (Gibson, 1966; Katz, 1989/1925). Later works, concerning memory in touch have also mentioned the relevance of movements (Kaas et al., 2008; Millar, 1999). Millar (1999) has even suggested the existence of a *movement loop* as a rehearsal system for touch that could be similar to the phonological loop for verbal material. This system would work as a mental rehearsal of the executed movements, maintaining a dynamic representation of the stimuli and of the exploration patterns. Earlier, within a serial recall paradigm, Gilson and Baddeley (1969) had also suggested the existence of some type of non-verbal rehearsal in haptic memory, even though no further studies were conducted to clarify the nature of these system.

Taking the present results into account, we can assume that a movement loop, or a system of tactile rehearsal that depends mainly on movement, does not seem to be a reliable explanation for tactile memory. As we shown, motor interference did not affect haptic recognition for common objects, revealing that the execution of distractor movements did not impair performance. One relevant aspect is, of course, the fact that participants performed the haptic study phase and the interference task with different hands. Nonetheless, a movement loop or a similar system should be affected by the execution of two complex movements, even if they were performed with different hands, since both tasks demanded for attentional resources, and none required an answer. Another aspect concerns the difficulty of designing a procedure that would allow to control for a movement interference in the same hand where the stimuli were being presented. Previous studies have shown that movement constriction has drastic consequences in recognition and identification (Lederman & Klatzky, 2004), and within that scenario, one could not differentiate the impairment that resulted from the lack of feature collection (considering that restricting a movement implies the loss of tactile discriminability) and the one that resulted from resource sharing (from a cognitive demanding task, not necessarily related to perceptual impediments).

Overall, the existence of a movement loop, or a system focused on movements to maintain tactile and haptic information in memory does not seem viable. The way tactile and haptic stimuli are perceived, processed and maintained in memory does seem to rely on tactile specific features, but these features are not limited to movement encoding.

EXPERIMENT 3: The Effect of Verbal Interference[7]

RESULTS

Corrected hit rates (hits minus false alarms) for haptic recognition are presented in Figure 5. A 2x2 ANOVA regarding object type (common or uncommon) and interference condition (no interference or verbal interference), revealed an object type main effect, F (1, 56) = 39.51, $p < .001$, $r = .638$, with common objects presenting better recognition rates that uncommon objects; and an interference main effect, F (1, 56) = 26.92, $p < .001$, $r = .570$, showing that verbal interference impaired participants' performance. A deeper analysis, using the Bonferroni correction ($\alpha = .050/2 = .025$) showed that verbal interference affected haptic recognition for uncommon objects [t (28) = 3.94, $p < .001$, $r = .597$], but not for common objects [t (28) = 1.51, $p = .143$, $r = .274$]. An interaction effect between the variables was also found, F (1, 56) = 5.44, $p = .023$, $r = .298$,

---

[7] Method for this experiment is described in the first and second articles in this thesis. Further information on the stimuli can be found in Appendices A, E, and F.

suggesting that haptic recognition of uncommon objects was more affected by verbal interference than haptic recognition of common objects.

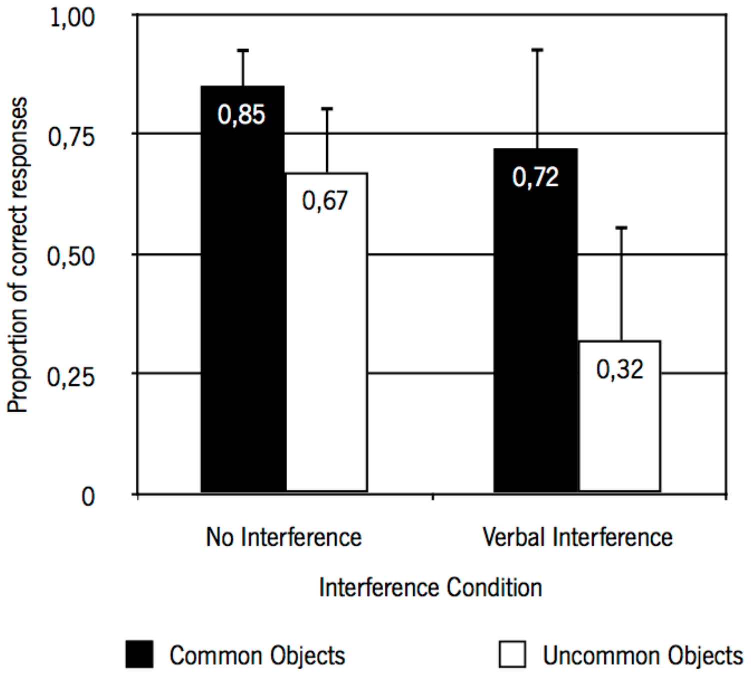

Figure 5: Corrected hits in haptic recognition with no interference and verbal interference according to object type

Analysing the B''D decision criteria in the recognition task (Donaldson, 1996), we can see no differences according to object type, *F* (1, 56) = .30, *p* = .59, *r* = .071; to interference tasks, *F* (1, 56) = .03, *p* = .88, *r* = .000; and there is no interaction effect between the variables, *F* (1, 56) = 2.68, *p* = .11, *r* = .214. Criteria in haptic recognition was the same in all experimental conditions.

The data for the verbal interference task shows that task condition (single verbal task or verbal task simultaneous with haptic study phase) did not affect performance, *F* (1, 28) = .049, *p* = .83, *r* = .045; and that explored object type did not affect participants performance in the interference task as well, *F* (1, 28) = .699, *p* = .410, *r* = .394. Also, no interaction effect was found between task condition and object type, *F* (1, 28) = .167, *p* = .685, *r* = .277. Table 4 presents the data for corrected hit rates in verbal interference task. These results assure that participants were following the instructions and focusing in the verbal task while in haptic study phase, and that haptic exploration of objects did not affect participants ability to respond to a simultaneous verbal task. As such one can assume that any variation in performance on the haptic task in due to verbal interference at encoding and not a result of an interaction effect in a simultaneous task condition.

Table 4: Corrected hits for verbal interference according to task condition and object type (standard deviations are presented between brackets)

	Verbal Interference Single-Task	Verbal Interference Dual-Task
Common Objects	.69 (.25)	.68 (.22)
Uncommon Objects	.72 (.14)	.75 (.22)

DISCUSSION

This experiment confirmed for verbal interference conditions the conclusion from previous experiments, in which haptic recognition for common objects is systematically better than haptic recognition for uncommon objects. Likewise, the interference task, had a greater impairment in haptic recognition for uncommon than for common objects, as shown by the interaction effect between object type and interference task.

Again, these results suggest that haptic recognition of everyday objects is robust, presenting high recognition rates for both types of objects, and revealing that haptic recognition of common objects is particularly robust.

This study results are congruent with Lacey and Campbell's (2006) finding that verbal interference at encoding affects participants recognition of unfamiliar objects in a crossmodal design. Contrary to Johnson, Paivio and Clark's (1989) suggestion, uncommon object recognition was affected by verbal interference, pointing that uncommon object processing is dependent on verbal cues or is verbally mediated as referred by Lacey and Campbell (2006). Considering that uncommon objects in this study were hardly identified in previous studies (see Appendix F), and presented low familiarity rates (see Appendix E), we can assume that participants are not identifying or correctly naming the touched stimuli. Alternatively, we argue that participants were tagging the stimuli according to specific object properties or even basing the verbal tag in wrong identifications of the objects. In fact, some participants mentioned thinking of the objects attending to tactile properties, for instance “a heavy and cold object”, or naming objects even when they were aware that it was not a correct identification, for instance calling the miniaturised helmet “a bell”.

As such, although participants were able to automatically identify the common objects when presented by touch, verbal encoding seems to have been more relevant for uncommon than for common objects. As mentioned earlier, common objects have robust representations, and binding between cues from different modalities can be automatic, this implies that touching an object elicits visual, auditory, verbal, and previous experiences with the objects, facilitating encoding. On the other hand, retrieval of uncommon objects might have been harder and implied a voluntary attempt to retrieve verbally tagged features of the objects. The disruption of these verbal encoding strategies by the simultaneous presentation of the verbal interference task might have impaired how well participants were able to encode each object, and force them to adopt different strategies (for instance, creating visual mental images).

EXPERIMENT 4: The effect of Visuospatial Interference[8]

RESULTS

Overall, haptic recognition of everyday objects was very effective. Figure 6 shows the mean values of corrected hits (hits minus false alarms) for each condition. Haptic recognition results corroborate a high efficacy of touch in recognition of everyday objects (Lederman & Klatzky, 1987).

An ANOVA 2x2 (object type: common or uncommon X interference condition: control or visuospatial interference) was conducted on corrected hits and revealed an object type effect, *F* (1, 56) = 39.89, *p* < .001, *r* = .645, with common objects always presenting better recognition rates than uncommon objects in the two conditions; a condition main effect, *F* (1, 56) = 33.57, *p* < .001, *r* = .612, showing that performance with visuospatial interference at encoding is worst than in control no interference condition; and no interaction between object type and task condition, *F* (1, 56) = 3.40, *p* = .07, *r* = .072. Exploring the results (applying the Bonferroni correction (α = .050/2 = .025) it is possible to observe that visuospatial interference impaired haptic recognition of uncommon objects, *t* (28) = 3.17, *p* = .004, *r* = .514; but not of common objects, *t* (17.2) = 1.72, *p* = .10, *r* = .376.

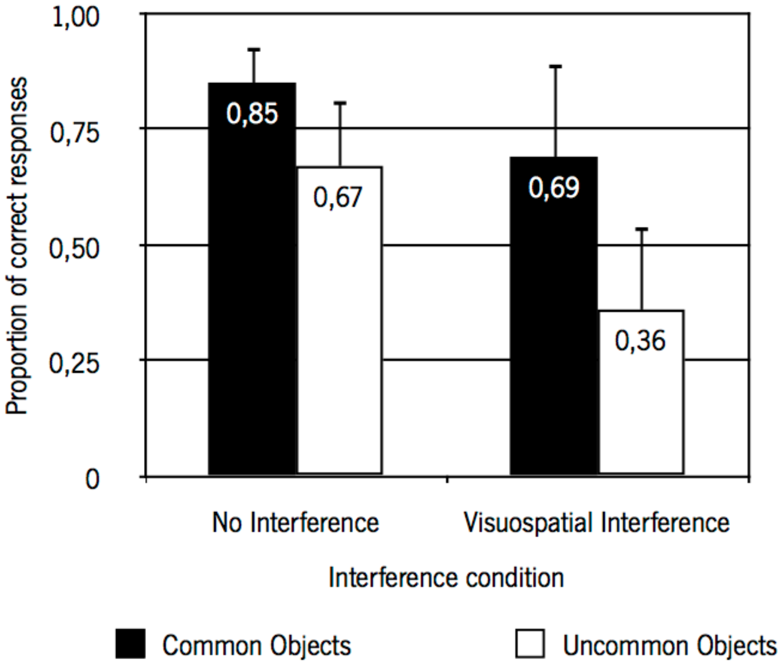

Figure 6: Corrected hits in haptic recognition with no interference and visuospatial interference according to object type

---

[8] Method for this experiment is described in the first and second articles in this thesis. Further information on the stimuli can be found in Appendices A, E, and F.

Looking into B''_D values (Donaldson, 1996) we can understand if there are any decision criteria variations in the haptic recognition task. Results show that participants were able to maintain their criteria across conditions. There are no differences in B''D according to object type, *F* (1, 56) = .03, *p* = .88, *r* = .000, to interference task, *F* (1, 56) = .92, *p* = .34, *r* = .126, and there are no interaction effects between the variables, *F* (1, 56) = .72, *p* = .40, *r* = .114.

Another interesting data regards participants’ performance on the visuospatial task in single and dual task conditions. Table 5 shows the results in visuospatial task according to each condition. Performance in the visuospatial interference task was also analysed recurring to a repeated measures ANOVA (Interference task condition: single or simultaneous with haptic study phase *vs* Object type: common or uncommon) on visuospatial performance (corrected hits). Results show no effect for interference task condition, *F* (1, 28) = . 29, *p* = .59, *r* = .100, demonstrating that, as intended, participants were focused in visuospatial task performance, being able to maintain an equivalent performance in both single and simultaneous conditions; there is also no effect for object type, *F* (1, 28) = .40, *p* = .53, *r* = .118, revealing that performance in visuospatial task was equivalent for common and uncommon objects; and there is no interaction effect between interference task condition and object type, *F* (1, 28) = .07, *p* = .79, *r* = .055. Considering these results, we can conclude that performance in the visuospatial task appears to be independent of performance in the haptic task, and that participants were able to concentrate on the visuospatial interference task while doing the haptic study phase. As such, results in haptic recognition can be attributed to visuospatial interference since there is no tradeoff effect between haptic and visuospatial task.

Table 5: Corrected hits for visuospatial interference according to task condition and object type (standard deviations are presented between brackets)

	Visuospatial Interference Single-Task	**Visuospatial Interference Dual-Task**
Common Objects	.56 (.35)	.52 (.31)
Uncommon Objects	.58 (.33)	.61 (.24)

DISCUSSION

This experiment confirmed the findings of the previous experiments: participants were able to present a corrected hit rate (hits minus false alarms) in recognition that was above .80 for common objects, and above .60 for uncommon objects, revealing that even with less familiar or hardly identifiable objects, we are able to perform at high rates with information collected by touch alone.

A demanding visuospatial interference task at encoding revealed a main effect, but in a deeper analysis showed no effect for common objects’ haptic recognition.

Haptic recognition of uncommon objects was more impaired by visuospatial interference than haptic recognition of common objects, a result congruent with the hypothesis that uncommon object recognition being more affected by a concurrent task. This result suggests that familiarity can modulate the cognitive processes associated with haptic memory. The low familiarity (see Appendix E) and identification (see Appendix F) of uncommon objects might have increased task difficulty, making these tasks more resource demanding than the common object tasks. The encoding of common objects might be easier considering that people are able to name them, have a mental image of them and have previous knowledge about how to manipulate them and about their weight, shape or temperature. Klatzky and Lederman (1995) mentioned the relevance of topdown processes in haptic identification, showing that previous knowledge about the item can influence its identification.

A visuospatial interference task was not able to disrupt performance in a recognition task with common objects, a result described in previous studies with less demanding tasks (Lacey & Campbell, 2006). Even considering the visuospatial nature of the present task, in contrast with the purely visual dynamic noise task (Darling, Sala, & Logie, 2009) presented by Lacey and Campbel (2006), we found no effect in haptic recognition of common objects, suggesting that haptic representations o common items are very robust not only to visual, but also to spatial interference.

GENERAL DISCUSSION

A consistent result in this study is the high performance on haptic recognition, both in no interference and interference conditions, and even with uncommon objects. This result highlights the efficacy of touch in perceiving and recognising three-dimensional everyday stimuli.

When analysing performance only for common objects we can observe that recognition rates are above chance even in interference conditions, demonstrating that participants are attending to a large set of cues during processing and that haptic memory can that can be quite resistant to interference from one specific type of information. In fact, only haptic interference resulted in a significant disruption of haptic recognition performance. The recognition of uncommon objects was good in control conditions, revealing that even when naming and visual representations are not immediate (the objects were unfamiliar and very hard to identify), participants are able to recognise the items.

A relevant result in this study is the pattern of the interference effects in haptic recognition for both common and uncommon objects. In all experiments, uncommon objects were more affected by interference than common object, although both types of objects' recognition was only affected by haptic interference, with verbal and visuospatial interference tasks not impairing recognition performance for common objects, and motor interference not affecting performance in recognition for both types of objects.

In the present data, we can observe that, for uncommon objects, haptic recognition after verbal interference at encoding was the condition that presented the worst performance. Opposite to the idea presented by Johnson et al. (1989) that unfamiliar object would have a visual representation (while familiar objects could present a visual and a verbal representation), this set of experiments showed that verbal encoding is very relevant in recognition of uncommon object, even though we cannot attribute a name to them.

These experiments provided an overview of haptic memory, considering performance in interference and no interference conditions at encoding, with common and uncommon objects, and in optimal conditions for haptic performance. Retrieval of information acquired by touch alone presented a high rate and common objects' representations were shown to be very robust, being impaired only by haptic interference. Uncommon objects' representations were not affected by motor interference, but haptic, verbal, and visuospatial interference disrupted performance.

Further exploration of haptic representations within dual tasks paradigms should focus on interference effects at other phases of processing, contributing to a better understanding of how we encode, process and retrieve information through touch.

REFERENCES

Anderson, J., Reder, L., & Lebiere, C. (1996). Working memory: Activation limitations on retrieval. *Cognitive Psychology*, 30, 221-256

Baddeley, A.D. (1999). *Essentials of human memory* (p. 356). Hove: Taylor & Francis Psychology Press.

Baddeley, A.D. (2000). The episodic buffer: a new component of working memory *Trends in Cognitive Sciences*, *4*(11), 417–423, doi: 10.1016/S1364-6613(00)01538-2

Baddeley, A.D., Allen, R., & Hitch, G.J. (2010). Investigating the episodic buffer. *Psychologica Belgica*, *50,* 223-243.

Baddeley, A.D. & Hitch, G.J. (1974). Working Memory. In G.H. Bower (Ed.) *The psychology of learning and motivation*. New York: Academic Press

Bliss, I., Kujala, T., & Hämäläinen, H. (2004). Comparison of blind and sighted participants' performance in a letter recognition working memory task. *Cognitive Brain Research*, *18*(3), 273–277. doi:10.1016/j.cogbrainres.2003.10.012

Bushnell, E.W., & Baxt, C. (1990). Children's Haptic and Cross-Modal Recognition With Familiar and Unfamiliar Objects. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(6), 1867–1881.

Cattaneo, Z., & Vecchi, T. (2011). *Blind Vision: The Neuroscience of Visual Impairment* (p. 288). The MIT Press.

Conway, A.R.A., & Engle, R.W. (1994). Working memory and retrieval: A resource-dependent inhibition model *Journal of Experimental Psychology: General*, *123*(4), 354–373. American Psychological Association. doi: 10.1037/0096-3445.123.4.354

Craddock, M., & Lawson, R. (2008). Repetition priming and the haptic recognition of familiar and unfamiliar objects. *Perception & Psychophysics*, *70*(7), 1350–1365. doi:10.3758/PP.70.7.1350

Craddock, M., & Lawson, R. (2009). The effects of size changes on haptic object recognition *Attention, Perception, & Psychophysics*, *71*(4), 910–923. doi:10.3758/APP.71.4.910

Darling, S., Sala, S.D., & Logie, R.H. (2009). Dissociation between appearance and location within visuo-spatial working memory. *Quarterly Journal of Experimental Psychology*, *62*(3), 417–425. doi:10.1080/17470210802321984

Deshpande, G., Hu, X., Lacey, S., Stilla, R., & Sathian, K. (2010). Object familiarity modulates effective connectivity during haptic shape perception. *NeuroImage*, *49*(3), 1991–2000. Elsevier B.V. doi:10.1016/j.neuroimage.2009.08.052

Donaldson, W. (1996). The role of decision processes in remembering and knowing. *Memory & Cognition*, *24*, 523-533.

Easton, R., & Srinivas, K. (1997). Do vision and haptics share common representations? Implicit and explicit memory within and between modalities. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 23,* 153-163.

Fernandes, A.M. & Albuquerque, P.B. (submitted a). Haptic recognition of common objects: The effects of interference at encoding.

Fernandes, A.M. & Albuquerque, P.B. (submitted b). Recognising uncommon objects by touch: effects of interference.

Gibson, J. (1966). The senses considered as perceptual systems. Oxford: Houghton Mifflin.

Gilson, E.Q., & Baddeley, A.D. (1969). Tactile short-term memory. *Quarterly Journal of Experimental Psychology*, *21*(2), 180–184.

Haag, S. (2011). Effects of vision and haptics on categorizing common objects *Cognitive Processing*, *12*(1), 33–39. doi:10.1007/s10339-010-0369-5

Johnson, C.J., Paivio, A.U., & Clark, J.M. (1989). Spatial and verbal abilities in children's crossmodal recognition: A dual coding approach *Canadian Journal of Psychology/Revue canadienne de psychologie*, *43*(3), 397–412. doi:10.1037/h0084229

Kaas, A., Stoeckel, M., & Goebel, R. (2008). The neural bases of haptic working memory. In M. Grunwald (Ed.), *Human haptic perception: Basics and applications* (pp. 113–129). Basel: Birkhäuser.

Katz, D. (1989). *The world of touch* (L. Krueger, Tran.) (p. 260). Hillsdale: Lawrence Erlbaum. (original work published in 1925).

Klatzky, R.L., & Lederman, S.J. (1995). Identifying objects from a haptic glance. *Percept Psychophys*, *57*(8), 1111–1123.

Klatzky, R.L., & Lederman, S.J. (1987). The Representation of Objects in Memory: Contrasting Perspectives from Vision and Touch. In M. Gruneberg & P. Morris (Eds.). Practical aspects of memory,Vol. 2, pp. 426–433. GB: Wiley

Klatzky, R.L., Lederman, S.J., & Metzger, V. (1985). Identifying Objects by Touch - an Expert System. *Perception & Psychophysics*, *37*(4), 299–302.

Lacey, S., & Campbell, C. (2006). Mental representation in visual/haptic crossmodal memory: evidence from interference effects. *Quarterly Journal of Experimental Psychology (Colchester)*, *59*(2), 361–376. doi: 10.1080/17470210500173232

Lacey, S., Flueckiger, P., Stilla, R., Lava, M., & Sathian, K. (2010). Object familiarity modulates the relationship between visual object imagery and haptic shape perception. *NeuroImage*, *49*(3), 1977–1990. doi:10.1016/j.neuroimage.2009.10.081

Lederman, S.J., & Klatzky, R.L. (1987). Hand movements: a window into haptic object recognition *Cognitive Psychology*, *19*(3), 342–368.

Lederman, S.J., & Klatzky, R.L. (2004). Haptic identification of common objects: effects of constraining the manual exploration process. *Percept Psychophys*, *66*(4), 618–628, doi: 10.3758/BF03194906

Loomis, J.M., Klatzky, R.L., & Lederman, S.J. (1991). Similarity of tactual and visual picture recognition with limited field of view. *Perception*, *20*(2), 167–177.

Millar, S. (1999). Memory in touch. *Psicothema*, 11(4), 747-767.

Norman, J.F., Norman, H.F., Clayton, A.M., Lianekhammy, J., & Zielke, G. (2004). The visual and haptic perception of natural object shape *Perception & Psychophysics*, *66*(2), 342–351, doi: 10.3758/BF03194883

Oberauer, K., & Göthe, K. (2006). Dual-task effects in working memory: Interference between two processing tasks, between two memory demands, and between storage and processing. *European Journal of Cognitive Psychology*, *18*(4), 493–519. doi:10.1080/09541440500423038

Paz, S., Mayas, J. & Ballesteros, S. (2007). Haptic and visual working memory in young adults, healthy older adults, and mild cognitive impairment adults. World Haptics Proceedings.

Wijntjes, M.W.A., van Lienen, T., Verstijnen, I.M., & Kappers, A.M.L. (2008). Look what I have felt: unidentified haptic line drawings are identified after sketching. *Acta Psychologica*, *128*(2), 255–263. doi:10.1016/j.actpsy.2008.01.006

PART II

CONCLUSION

The present studies are a first attempt to systematically explore haptic memory with a classical paradigm as is the dual-task procedure. The design of these experiments required a significant effort to build interference tasks that would be equivalent, both in performance time, as in difficulty (cf. Appendices B, C, and D). At the same time, the robustness of haptic memory, congruent with the findings of some perceptual studies (e.g. Klatzky, Lederman, & Metzger, 1985), but incongruent with existent memory studies (e.g. Gallace, Tan, Haggard, & Spence, 2008; Gilson & Baddeley, 1969), demanded caution in the selection of the haptic stimuli and of the haptic presentation procedures.

Our results showed a very robust memory, almost undisrupted by interference for common objects, and, although less robust for uncommon objects, still very effective, with recognition values above chance in all the experimental conditions.

Data for common objects reveals that only a haptic interference task (that consisted in the evaluation of paper samples), was able to impair haptic recognition. Haptic interference implied the coordination of two different tasks, performed with each hand - object exploration with the non-dominant hand, and paper evaluation with the dominant hand. However, haptic interference was not the consequence of a coordination problem, since the motor interference, that required the execution of exactly the same movements, did not impaired haptic recognition. This result implies that haptic interference was a result of the cognitive task, maybe due to resource sharing between the two tasks, and not just an effect of a more complex or demanding perceptual or motor sequence of movements. Another result was that neither verbal nor visuospatial interference at encoding resulted in haptic recognition impairment. This result is particularly interesting regarding the nature of these stimuli. Common objects were easily identifiable and were evaluated as familiar in previous studies (c.f. Appendices E and F). Considering these previous data, we can assume that participants were able to give a name to the touched object, and to create a mental image of the same object. Nonetheless, participants did not seemed to be relying on these cues to recognise the objects, since neither task had an effect in haptic recognition. Moreover, the haptic interference condition, in which the participants could be rehearsing the stimuli through verbal and visuospatial codes, showed a drastic impairment in haptic recognition, with these (verbal / visuospatial) strategies either not being used, or not being sufficient to differentiate touched from non touched objects during recognition.

Uncommon object's recognition analysis has a particular interest. These stimuli were hardly identified by participants in previous studies (c.f. Appendix F), and were also evaluated as unfamiliar (c.f. Appendix E) - objects that the participants use not so often. With this set of stimuli one would expect that both naming and visual imagery would be unlikely and would require a large amount of effort - participants would have to create a name tag and intentionally associate that name tag to the stimuli, or would have to construct a mental image of the object, based on perceived shape, for instance, and relate that image with that specific stimuli. Likewise, a haptic schema of the touched objects would be demanding, since the participants would have to actively encode and group tactual features the were not bound automatically for these stimuli. Considering that both the haptic study list and the recognition list were composed by 50 objects, these type of strategies would clearly be very demanding. Results obtained with these stimuli confirm these predictions - even in no interference conditions, participants' recognition is lower than common objects recognitions. Not only verbal and visuospatial interference impaired recognition, but also haptic and even motor interference affected recognition performance. Curiously, in haptic interference, we also found a tradeoff effect, with haptic exploration of the objects in the study phase impairing the participants' ability to discriminate between the paper samples. This result indicates that there might occur resource sharing between the two touch-related tasks, that is inexistent in the verbal and visuospatial tasks.

Finally, we close this set of studies by reanalysing the data directly comparing common and uncommon objects in each interference condition. These results show the expected advantage of common over uncommon object recognition, and reveals some interaction effects, in which uncommon objects tend to be more affected by interference than common objects. The nature of the differences between the two types of objects might be mediated by stimuli familiarity (Lacey, Flueckiger, Stilla, Lava, & Sathian, 2010), but is also responsible for an increased difficulty in the tasks, that is due not only to the interference conditions, but also to the absence of a previous representations for the uncommon stimuli.

Overall, we can conclude that haptic memory seems to have modality-specific features, and can rely on tactual properties, extracted from the stimuli, like temperature, weight, texture, size and shape. These haptic features can be encoded and stored in memory, and allow participants to discriminate between presented and non-presented items, even when fine differences are being analysed.

Although it is true that in everyday experience humans mostly experience multimodal stimuli, and as such the perception and encoding of stimuli, and everyday objects in particular, is essentially multimodal, it is crucial to understand and explore the processing in unimodal conditions to better understand the contributes of each modality and to examine how each sensory modality perceives and processes information in the absence of multimodal cues. Touch, like other modalities, allows us to perceive unique features, like temperature and weight, which are relevant for the way we perceive stimuli. Moreover, movement perception is one of the senses of touch, and an essential ability for interactions with the surrounding environment, determining actions like grasping.

REFERENCES

Gallace, A., Tan, H.Z., Haggard, P., & Spence, C. (2008). Short term memory for tactile stimuli. *Brain Research*, *1190*, 132–142. doi:10.1016/j.brainres.2007.11.014

Gilson, E.Q., & Baddeley, A.D. (1969). Tactile short-term memory. *Quarterly Journal of Experimental Psychology*, *21*(2), 180–184.

Klatzky, R.L., Lederman, S.J., & Metzger, V. (1985). Identifying Objects by Touch - an Expert System. *Perception & Psychophysics*, *37*(4), 299–302.

Lacey, S., Flueckiger, P., Stilla, R., Lava, M., & Sathian, K. (2010). Object familiarity modulates the relationship between visual object imagery and haptic shape perception. *NeuroImage*, *49*(3), 1977–1990. doi:10.1016/j.neuroimage.2009.10.081

Familiar

A ciência não caminha em direcção ao mistério. Nem em direcção ao Estranho.
A ciência caminha em direcção ao Familiar.

Gonçalo M. Tavares, *em Breves notas sobre ciência*

PART III

INTRODUCTION

Memory capacity, either defined as the time one can hold an item on memory, either as the maximum number of items one can remember for a short period, has been a topic of interest in memory theory and research. In this third part of the thesis we will explore the limits of haptic memory regarding the number of items that one can maintain in memory for a short period of time.

Miller (1956) presented a classical work on memory, revealing that the estimated capacity of short term memory was of approximately seven items. More recently, Cowan (2001) suggested a readjustment of the average capacity to four items, attending to the relevance of long-term memory involvement in short term memory tasks, and to the processes of online memorisation and rehearsal. In conditions in which the stimuli do not allow this type of elaborate processes (e.g., information overload), the average capacity falls down to three to five items or chunks (Cowan, 2001).

Former research has indicated that haptic memory presents a smaller item capacity than other types of memory, namely visual (e.g., Gallace & Spence, 2009). However, no other study has explored haptic capacity for everyday objects in free exploration conditions. From previous literature we were able to comprehend that touch is an *expert system* (e.g., Klatzky, Lederman & Metzger, 1985) and that people are much better at recognising and identifying everyday objects than abstract or unreal items (e.g. Klatzky, Loomis, Lederman, Wake, & Fujita, 1993). As such, it becomes essential to explore haptic span for complex objects in naturalistic conditions to analyse if haptic span is in fact smaller than span in visual and auditory modalities.

Taking into consideration that time (processing time, retention interval or stimuli exposure duration) is a central variable in span tasks, the design of haptic span experiments might be complex, and any data interpretation needs to be cautious at such a premature stage in haptic working memory capacity research. We need to ponder all variables at stake: type of stimuli, haptic exploratory procedures, manipulation times, inter-stimulus intervals, list size, and type of retrieval task. As we have seen in the previous studies, the effect of verbal interference in haptic working memory did not seem to affect haptic recognition of common objects, while it affected recognition of uncommon objects. Attending to the fact that common objects in our set are easily identified (c.f. Appendix F), this result is interesting, and we decided to explore it within the memory span paradigm, attempting to replicate and clarify this (lack of) effect.

The following experiments represent a first attempt to evaluate haptic span for everyday objects and analyse the impact of verbal encoding of these type of stimuli in memory performance. We adapted two central memory span paradigms: serial recall (e.g., Conrad & Hull, 1968) and reconstruction of order (e.g., Neath, 1997) and evaluated participants' performance with common and uncommon objects in single conditions and under articulatory suppression condition.

The data will be explored, attending to patterns of response, type of errors, and differences between experimental conditions. The main contribution of these studies are their implications for future work on haptic span. Presenting a first approach to the topic, we attempted to control for a group of variables that previous literature had identified as central in haptic memory. Regarding the results of these experiments we will elaborate on the nature of haptic memory, and draw implications for future research.

REFERENCES

Conrad, R., & Hull, A. (1968). Input Modality and Serial Position Curve in Short-Term Memory. *Psychonomic Science*, *10*(4), 135–136.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, *24*(1), 87–.

Gallace, A., & Spence, C. (2009). The Cognitive and Neural Correlates of Tactile Memory. *Psychological Bulletin*, *135*(3), 380–406. doi:10.1037/a0015325

Klatzky, R.L., Loomis, J.M., Lederman, S.J., Wake, H., & Fujita, N. (1993). Haptic identification of objects and their depictions. *Perception & Psychophysics*, *54*, 170–170.

Klatzky, R.L., Lederman, S.J., & Metzger, V. (1985). Identifying Objects by Touch - an Expert System. *Perception & Psychophysics*, *37*(4), 299–302.

Miller, G. (1956). The magical number seven, plus or minus two: some limits on our capacity for processing information *Psychological Review*.

Neath, I. (1997). Modality, concreteness, and set-size effects in a free reconstruction of order task *Memory & Cognition*, *25*(2), 256–263.

PART III

SPAN TASKS: Experimental Work

Explorations on haptic memory span:
Immediate recall and reconstruction of order tasks[9]

ABSTRACT

This study reports two exploratory experiments on haptic memory span for everyday objects. Using two different paradigms, immediate serial recall (Experiment 1) and reconstruction of order (Experiment 2), we intended to evaluate haptic memory span. In Experiment 1 haptic modality performance for common objects was accessed. In Experiment 2, haptic span for common and uncommon objects was estimated. The relevance of verbal encoding of haptic information was explored by requiring each participant to perform the span tasks in single and articulatory suppression conditions in both Experiment 1 and 2.

Results indicated that, for immediate serial recall, participants were able to retrieve an average of five items in single task conditions and four items in articulatory suppression conditions; and in reconstruction of order tasks about six items in single task and five items in articulatory suppression. Overall, reconstruction of order performance was better than immediate serial recall performance,

The classic work of Miller (1956) defined the maximum number of items one could recall after a brief presentation as seven plus or minus two. The concept of chunking - grouping items together in order to facilitate rehearsal and integrate information - brought further knowledge into how we perceive information increasing accuracy in recall (Miller, 1956). More recently, Cowan (2001) suggests that our memory capacity is of about four items or information chunks in conditions in which long-term memory facilitation of span tasks is controlled for. In span tasks, short-term and long-term memory are connected, since our ability to recall sentences has been shown to be a lot greater than our ability to recall unrelated words, suggesting information exchange between short-term and long-term memory in span tasks (e.g., Saint-Aubin & Poirier, 1999).

Three central tasks have been described in the literature to measure memory span: *free recall*, *immediate serial recall*, and *reconstruction of order*. In free recall tasks, the participants are asked to recall all the items presented in a list in the order they prefer. Immediate serial recall, on the other hand, consists in recalling the previously presented items in the exact order of presentation, usually starting by the first element. Finally, in reconstruction of order tasks all the items presented in the lists are available at recall, and participants have to reorder the items, making them correspond to the initial presentation.

Results in free recall and immediate serial recall tasks tend to be similar, suggesting similar strategies in rehearsal and recall for both tasks (Bhatarah, Ward, Smith, & Hayes, 2009). However, free recall frequently produces two distinct effects in the serial position curve plots: a *primacy effect* that corresponds to a better

---

[9] Paper *in preparation*

recall of the first presented items and translates the initial burst of attention from the participants (Tan & Ward, 2008); and a *recency effect*, a better recall of items presented at the end of list when compared to the items in the middle, that corresponds to a direct output of information still present in short-term memory (Atkinson & Shiffrin, 1968).

There is a reported modality effect in free recall (e.g., Conrad & Hull, 1968) that shows larger recency effects for lists of words with auditory presentation, in comparison with the same words presented visually. This modality specificity contributed to the assumption that the recency effect was caused by a sensory trace in short-term memory, with auditory memory presenting longer durations than visual memory.

Immediate serial recall is usually presented as a procedure for estimating the capacity of short-term memory (Baddeley, Thomson, & Buchanan, 1975), and while this task is thought to require the recall of two types of information about the items, identity of the item and position information, in reconstruction of order tasks only information about the item position is necessary, since the items are all available at recall (Crowder, 1976). However, although identity information is not essential to perform the tasks, it is still processed by the participants and can affect performance (Neath, 1997). In this study Neath (1997) shows that modality, concreteness, and set-size effects affect performance in reconstruction of order tasks, arguing that this type of tasks are not pure measures of memory for order as had previously been argued (e.g., Whiteman, Nairne, & Serra, 1994). The assumption that the item is always its best retrieval cue is not necessarily true (Tulving, 1983), and this might be the case in reconstruction of order tasks.

Span tasks are frequently associated with short-term memory paradigms. However the dissociation between the concepts of short-term and working memory is not always clear. During this work we will use the Unsworth and Engle's (2007) classification, considering that the difference between short-term and working memory lies on the type of task designed to measure it. As such, short-term memory would be evaluated in single task conditions, like digit span, implying the retrieval of simple information (e.g. pure repetition of previous information); and working memory would be measured through more complex tasks involving the intervention of the central executive, like the inverse digit span, implying stimuli manipulation (Unsworth & Engle, 2007). In the present work, considering that besides item information, the participants are asked to retrieve order information about the item, which requires manipulation of information, since the participants have to recall the items in a sequence, we will define our tasks as working memory span tasks.

Span tasks in haptic memory have been used essentially in passive stimulation conditions with abstract stimuli such as vibration. This type of tasks have focused in the retrieval of location information instead of item information (e.g., Gallace, Tan, Haggard, & Spence, 2008; Gilson & Baddeley, 1969; Miles & Borthwick, 1996; Sullivan & Turvey, 1974). Results in these experiments have been contradictory with reports of no decay functions for tactile information (e.g., Kiphart, Auday, & Cross, 1988) and notice of decay (e.g., Millar, 1972), and sometimes reporting recency effects (e.g., Watkins & Watkins, 1974), and others showing no such effect (e.g., Miles & Borthwick, 1996).

Traditionally, tactile and haptic memory have been studied in the context of sensory registers. To our knowledge, no previous work intended to explore haptic or tactile memory span for everyday objects. Previous research has revealed that we are very good at identifying objects by touch only (Klatzky, Lederman, & Metzger, 1985), and also at recognising them (e.g., Craddock & Lawson, 2009, Klatzky & Lederman, 2003; Nabeta & Kusumi, 2008). These results are in clear opposition with data obtained from experiments in which participants need to recognise or recall haptically presented two-dimensional stimuli or abstract three-dimensional stimuli in which participants' performance is not as accurate (e.g., Wijntjes, van Lienen, Verstijnen, & Kappers, 2008).

The nature of processing of haptic information is not yet sufficiently explored and while some authors argue in favour of haptic specificity in memory (e.g., Kaas, Stoeckel, & Goebel, 2008) others assume a general modality-independent memory process (e.g., Baddeley & Hitch, 1974).

The relevance of verbal labels when we present familiar objects as stimuli is crucial (e.g., Bushnell & Baxt, 1999). With common stimuli, naming is almost automatic, and as such it is predictable that verbal encoding might take place. Also, even with uncommon stimuli verbal descriptions have been shown to aid item recognition (e.g., Lacey & Campbell, 2006). As such, the possibility of verbal encoding of haptic information must be considered in memory tasks, either with common or uncommon objects.

In the present study we investigate how many everyday objects one can recall in immediate serial recall and reconstruction of order tasks when the stimuli are presented in active touch conditions. Using everyday objects as stimuli, the impact of verbal interference (articulatory suppression) during encoding was considered of particular relevance, since the haptic identification of these stimuli was very high (c.f. Appendix F). To further explore the extent to which verbal encoding could facilitate memory span for stimuli presented by touch only, we decided to include a reconstruction of order task that would not imply the verbal retrieval of information (the stimuli are available at retrieval and as such the participants should only need to retrieve order information). Not requiring object identification, reconstruction of order tasks allowed the inclusion of a new condition: uncommon everyday objects. The comparison of performance with common and uncommon objects can also be useful to explore the impact of verbal (name) encoding in a haptic task, since uncommon objects showed lower familiarity (c.f. Appendix E) and identification (c.f. Appendix F) rates.

EXPERIMENT 1: Immediate Serial Recall

METHOD

Participants

Fifteen volunteers with a mean age of 22.7 (*SD* = 3.4), six male, students and former students of University of Minho participated in the experiment, whether for course credits (psychology students) or for a draw of a voucher at an electronics and book store.

Design

Immediate serial recall tasks implied a verbal recall of the presented stimuli (name), and as such required that the stimuli were identified and verbally retrieved from memory. To explore if this verbal retrieval would be impaired by verbal interference, each participant performed the span task in single task and in articulatory suppression conditions, having to repeat out loud the sequence "one, two, three, four" without interruption while the stimuli were being presented. The order of the articulatory suppression task was counterbalanced across participants.

The stimuli set was divided in two and each one of these subsets was presented in each condition for the same participant (single task or articulatory suppression task), avoiding repetition of objects between conditions. The set presentation was also counterbalanced, with each set being presented half the times in single task, and half the times in articulatory suppression task conditions.

Stimuli and materials

The experimental set up included a wooden box (with two openings: one facing the experimenter and another facing the participants that was covered by a cloth to prevent visual contact with the stimuli); and headphones through which the participant's heard white noise to mask any exploration sounds.

Haptic common objects were a set of 20 everyday objects selected from previous studies, presenting 100% correct identification in haptic tasks as can be confirmed in Appendix F (object set one included: notepad, knife, ball, stapler, cloth, calculator, toothbrush, lollipop, coffee cup, and tweezers; set two included: saucer, doll, lamp, pacifier, screw, spoon, mobile phone charger, cloth pin, PC mouse, and shoe brush). All the presented objects were small enough to allow exploration with only one hand and allowed silent manipulation.

Procedure

Participants sat in an adjustable stool in front of a table and placed both hands inside the wooden box and the stimuli were placed directly on their non-dominant hand. Participants were allowed to explore the stimuli freely, with both hands. Participants touched each stimuli for three seconds, with an inter-stimulus interval of five seconds, and the exploration times were marked by sound cues.

Every participant started at a two stimuli extension and could reach a maximum of ten stimuli. Participants' could respond up to three lists in each extension - when the participant correctly recalled two lists of an extension, the next extension was presented, and whenever the participant's missed two lists of the same extension, the experiment was terminated.

Before each phase (single task and articulatory suppression task) there was a training trial with an extension of two stimuli: in each condition the participants's task was to recall, in the correct order, the presented stimuli by saying their name out loud.

RESULTS

The span value corresponds to the maximum extension that the participants' recalled entirely correct.

Participants' global span results are presented in Figure 7. It is possible to observe that articulatory suppression condition resulted in worst performance than single task condition, *t* (14) = 4.2, *p* = .001, *r* = .745.

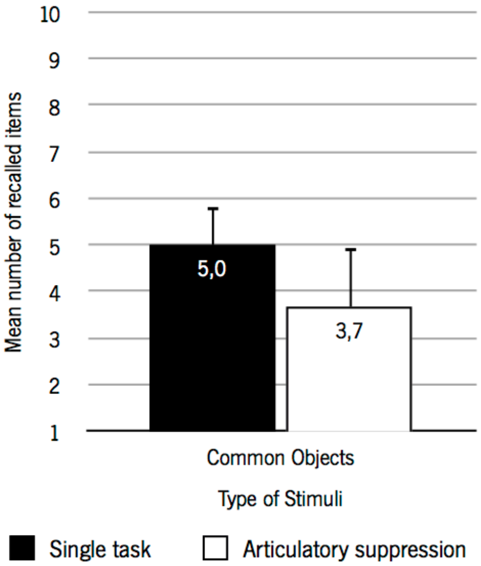

Figure 7: Mean span values in immediate serial recall according to task condition

Further exploring the span data, the participant's response patterns were examined in function of their performance level in single task condition. We intended to analyse if both high span and low span participants were equally affected by the articulatory suppression task. Dividing the sample in half (N = 15), and removing the participant with the middle value (in order to obtain an equivalent number of participants in each group - seven in high level performance and seven in low level performance) we can observe that, as expected, the participants are different according to performance on the single span task [*t* (12) = 3.2, *p* = .008, *r* = .679]. Figure 8 shows span results according to the participant's level of performance in single task conditions. A 2x2 (task condition: single task and articulatory suppression task *vs* performance level in single task: high span and low span participants) repeated measures ANOVA was conducted and showed a main effect of task condition *F* (1, 12) = 15.19, *p* = .002, *r* = .758, with articulatory suppression impairing performance; no main effect of performance level, *F* (1, 12) = 2.27, *p* = .158, *r* = .397, showing that participants' overall performance was equivalent, and no interaction effect, *F* (1, 12) = 1.69, *p* = .218, *r* = .467, showing that both high level and low level performers were affected by articulatory suppression.

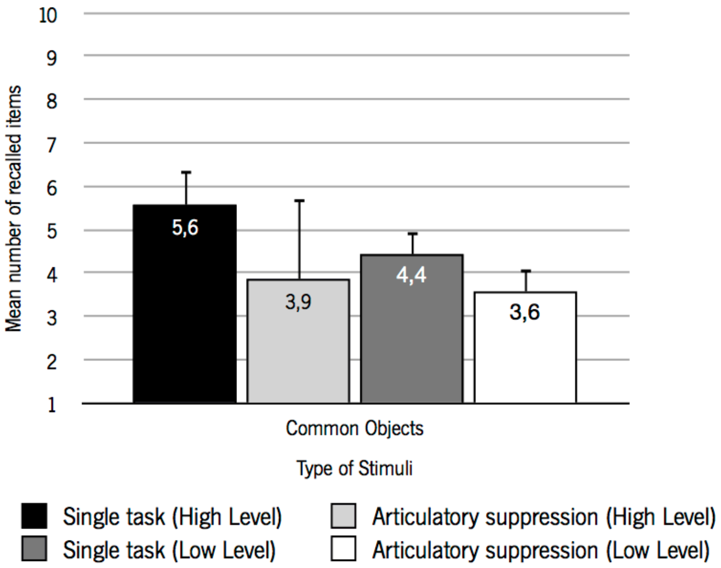

Figure 8: Mean span values presented as a function of high and low level performance in single task, according to task condition

A deeper analysis of the data is obtained by examining the type of errors the participants carried out in recall. Three main types of errors were considered: *omission* errors, when the participants failed to report an item in a list, *intrusion* errors when participants recalled an item that was not presented on the list, and *order* errors, when the participants reported a correct item, but placed it in an incorrect position in the list. A total of 79 errors were detected in single task condition, and a total of 73 errors were found in the articulatory suppression condition. Order errors were the most common (41 errors in single task condition and 38 errors in articulatory suppression condition), followed by omission errors (25 in single task condition and 26 in articulatory suppression condition), and intrusion errors (13 in single task and nine in articulatory suppression). Although the overall number of errors in the two conditions seems similar, it is important to notice that, in total, there are more participants contributing to the overall number of errors in single task conditions than in articulatory suppression conditions, since more participants were able to respond to larger lists in single task (e.g., in extension five, there were 14 participants in single task condition, but only seven in articulatory suppression). As such, the mean ratio of errors/participant is higher in articulatory suppression condition.

DISCUSSION

Haptic span for common everyday objects in immediate serial recall conditions was of about five items for single task conditions and about four items in articulatory suppression conditions, and results showed that articulatory suppression significantly impaired haptic performance. The mean span results seem to be equivalent to the ones obtained with visual and auditory presentations (e.g. Miller, 1956).

In the immediate serial recall task, verbal processing was mandatory, since participants were required not only to identify the touched objects, but also to recall their names in the retrieval task. In these conditions, verbal rehearsal is expectable to occur and the impact of articulatory suppression predictable. It was possible to observe, that participant's were affected by articulatory suppression regardless of the level of performance they showed in single task conditions. As such, the impact of articulatory suppression seems to be independent of the level of performance.

The exploration of the number of errors in recall showed a higher proportion of errors in articulatory suppression tasks, compared with single task condition. It is important to notice that the number of participants that were able to correctly recall all the items in longer extensions was larger for single task than for articulatory suppression conditions. These results confirm the impairment of performance due to the articulatory suppression task while the items were being presented.

Experiment 2 will analyse the relevance of verbal encoding in a task that does not imply item identification, and will allow a direct comparison between immediate serial recall and reconstruction of order with haptically presented everyday objects.

EXPERIMENT 2: Reconstruction of Order

METHOD

Participants

Thirty participants, students and former students at University of Minho took part is this experiment. The mean age of the participants was of 23.2 (*SD* = 5.4), and eight were male. Participants were offered course credit (psychology students) or inclusion in a draw for an electronics store voucher (former students and student from other graduations). These participants did not took part in the previous experiment.

Design

Participants were randomly distributed to one of two conditions, depending on object type: haptic common objects and haptic uncommon objects, with 15 participants in each group.

The reconstruction of order task, not requiring the naming of the stimuli, allowed for the comparison of performance with common and uncommon objects. With this procedure it was possible to analyse if the common object's retrieval advantage, described in literature and in the studies in the second part of this thesis (Fernandes & Albuquerque, submitted a; Fernandes & Albuquerque, submitted b), would also be present in this task. Reconstruction of order, not requiring the retrieval of specific information of the stimuli (Whiteman et al., 1994) should not show differences between common and uncommon objects presentation, since participants would only need to retain order information. On the other hand, if stimuli identity information is retained, even not being required to complete the task (Neath, 1997), then a difference in performance between common and uncommon objects should be expected.

Each participant performed the task in single task condition and in articulatory suppression conditions, having to repeat the sequence "one, two, three, four" without interruptions while the stimuli were being presented. The articulatory suppression condition was counterbalanced across participants.

Each stimuli set (common and uncommon objects) was divided in two. Each one of these sets was presented in each condition for the same participant (single task or articulatory suppression task) avoiding object repetition between conditions. Stimuli set presentation was counterbalanced, with both sets being presented in single task and articulatory suppression conditions.

Materials and Stimuli

The experimental set-up consisted in a wooden box (with two openings, one facing the experiment, and the other one facing the participant and being covered by a white cloth that prevented the participants from seeing the stimuli). During the experiment the participants wore headphones that produced white noise to prevent the detection of any exploration sounds. A computer was used to present sound cues that timed the beginning and ending of stimuli exploration.

Common objects were the same objects from Experiment 1 and uncommon objects were selected from previous studies and presented less than 13% of correct identifications as can be observed in detail in Appendix F (set one consisted of: plastic chilli, miniaturised ceramic hat, lipgloss package, miniaturised mop, miniaturised plastic glass, stapler remover, miniaturised plastic hairdresser, miniaturised helmet, miniaturised ashtray, and small hourglass; and set two consisted of: calculator, plastic screwdriver, plastic miniaturised maize ear, garlic peeler, plastic robot toy, miniaturised photo machine, miniaturised duct tape dispenser, miniaturised liquid soap package, and miniaturised perfume bottle). All objects were small enough to be explored with only one hand, and allowed silent manipulation.

Procedure

Participants sat in an adjustable stool and placed both hands inside the wooden box, with their non-dominant hand facing up. Haptic exploration was conducted freely with both hands, and each object was directly placed in the participant's non-dominant hand palm. The participants touched each object for three seconds, with a five seconds inter-stimuli interval. After each list, all the touched objects were randomly inserted in the box at the same time and the participants had to return them to the experimenter in the initial order, without seeing them. The participants began the task with a training list composed by two objects and then initiated the experiment with lists with the extension of two items. Participants could complete up to three lists in each extension. After correctly ordering the items of two lists, a list of the following extension was presented. If the participants failed to correctly order the items of two list in the same extension, the procedure was terminated. Each participant performed the task in single task and articulatory suppression conditions.

RESULTS

The haptic span values correspond to the maximum extension the participant was able to complete without errors. Reconstruction of order task performance was analysed in a 2x2 repeated measures ANOVA (stimuli type: haptic presentation of common or uncommon objects x task condition: single task or articulatory suppression). Results show a task condition effect, *F* (1, 28) = 8.2, *p* = .008, *r* = .476, with articulatory suppression significantly impairing performance; and no type of stimuli effect, *F* (1, 28) = 0.5, *p* = .487, *r* = . 130, with common and uncommon objects revealing a similar span; nor an interaction effect between the variables, *F* (1, 28) = 0.2, *p* = .663, *r* = .083.

However, exploring the effect of task condition within each of the object types (using Bonferroni's correction α = 0.05 / 2 = 0.025), no effect of articulatory suppression was found for common objects, *t* (14) = 1.91, *p* = .077, *r* = .457, nor for uncommon objects, *t* (14) = 2.14, *p* = .051, *r* = 496. Data is represented in Figure 9.

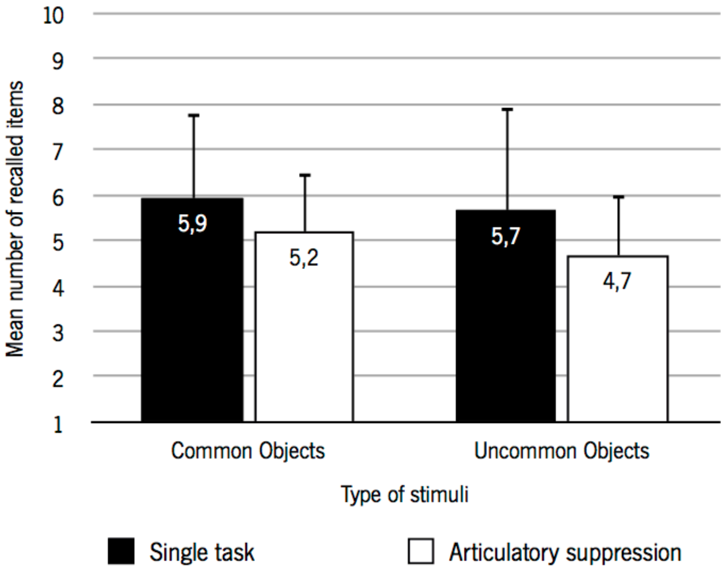

Figure 9: Mean span values in reconstruction of order according to type of stimuli

To analyse if the articulatory suppression task resulted in different patterns of response according to the participants' performance level, the sample was divided according to performance in the single span task, a 2x2x2 repeated measures ANOVA (performance level: high level performers and low level performers x stimuli type: haptic common objects, haptic uncommon objects x task condition: single task or articulatory suppression task) was performed. Figure 10 shows the results.

Results show a task condition effect, F (1, 24) = 15.8, $p = .001$, $r = .629$, with span values being higher for single task than for articulatory suppression conditions; a performance level effect, F (1, 24) = 18.1, $p < .001$, $r = .656$, with low level performers having overall smaller spans than high level performers; and no stimuli type effect, F (1, 24) = .673, $p = 420$, $r = .164$, with performance with common and uncommon objects being equivalent. An interaction effect between task condition and performance level was detected, F (1, 24) = 27.5, $p < .001$, $r = .731$, with articulatory suppression impairing reconstruction of order to a higher degree in high level performers, than in low level performers. No interaction effects were reported for task condition and stimuli type [F (1, 24) = 0.6, $p = .435$, $r = .161$], for performance level and stimuli type [F (1, 24) = 0.1, $p = .712$, $r = .077$], nor for task condition, performance level and stimuli type [F (1, 24) = 2.0, $p = .166$, $r = .279$].

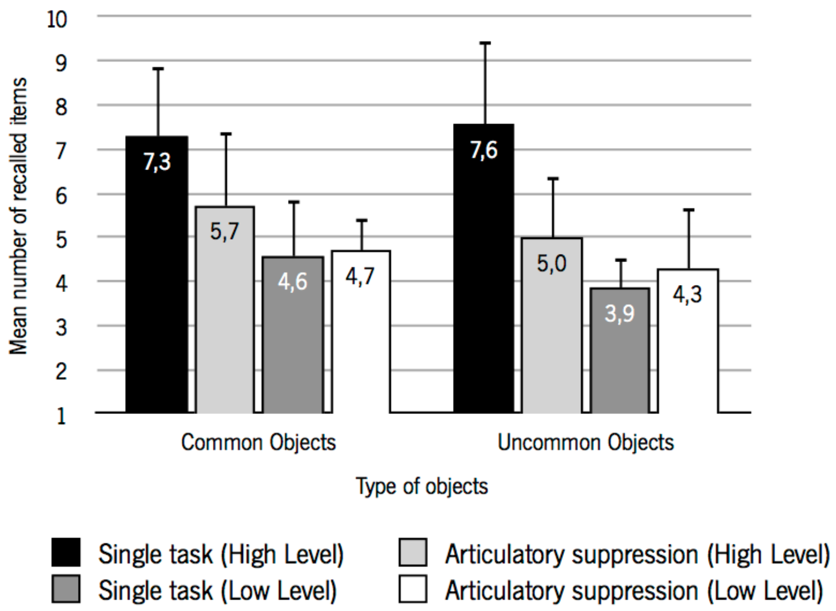

Figure 10: Mean span values presented as a function of high and low level performance in single task, according to task condition and type of stimuli

The error analysis in this task is focused in order errors, since intrusion and omission errors were not possible when all the touched objects were available during the memory test. Overall, uncommon objects presentation resulted in more errors than common objects presentations. In single task, uncommon objects present a total of 83 errors, while common objects show a total of 59 errors. Likewise, in the articulatory suppression task, uncommon objects originated 84 errors, and common objects' 54 errors. Once again, the total number of participants in each list in smaller for single task than for articulatory suppression, since less participants were able to respond to the larger extensions in articulatory suppression than in single task conditions. Although no stimuli type effect was detected, when the span values were examined, the error analysis shows that common objects produced a pattern of less errors than uncommon objects, suggesting a facilitation effect of familiarity, in reconstruction of order tasks.

DISCUSSION

In reconstruction of order memory tasks the haptic span for common objects was of about six items in single task conditions and of about five items in articulatory suppression conditions. Although articulatory suppression presented lower span results than single task condition, its effect was not robust, with span being equivalent in both tasks conditions either for common or uncommon objects, revealing that in reconstruction of order, the contribution of a verbal component was less important than in the immediate serial recall task, that implied the retrieval of stimuli by name.

Comparing performance for common and uncommon objects suggests two main conclusions. First, the type of object seemed to interfere with the amount of errors participants committed, showing a facilitation effect of familiarity, with common objects resulting in less errors than uncommon objects, although the overall spans were equivalent for both types of objects.

The lack of a robust articulatory suppression effect in this task is interesting due to the nature of the presented stimuli and the easy identification of common objects. The use of verbal descriptions is very common in our everyday life, and during our experiments we were able to confirm with the participants that they were using verbal labels to memorise the uncommon stimuli. In a short individual debrief with participants in the uncommon objects task, we were able to note that most participants either used a verbal tag for the object, that was frequently associated with haptic properties (e.g., *the smallest object, the cold object*), or even an incorrect identification that was associated with each stimuli (e.g., naming a miniaturised broom as a brush). However these strategies do not appear to have a significant impact in a reconstruction of order task. On the other hand, considering that common objects' representations are more robust (Lacey & Campbell, 2006) there are more available strategies for their rehearsal (e.g., representations elicited from touch, vision, audition or even from more complex processes as identification and categorisation).

Another interesting finding was that high level performers (participants with the higher spans in single task conditions) were more affected by articulatory suppression than low level performers. This result replicates work in our laboratory with visual and auditory stimulation, that revealed the same pattern of results (Oliveira & Albuquerque 2010a; Oliveira & Albuquerque 2010b) and was interpreted as being the consequence of better allocation of resources or adequate strategies in high-level than in low-level performers. This study suggested that the differences in span performance are not differences in memory capacity *per se*, but differences in the ability to allocate resources for a specific task. As such, differences in performance might me more associated with central executive functioning than with each memory store processing capacity.

GENERAL DISCUSSION

These experiments had a clear exploratory nature. No other study has aimed to define haptic span for everyday objects. The two experiments allowed the identification of haptic memory span recurring to two paradigms, and resulted in an haptic immediate serial recall span of five items for single task conditions and of four items in articulatory suppression conditions for common objects. In reconstruction of order tasks it was possible to obtain a haptic span for either common or uncommon objects of six items in single task condition and of five items in articulatory suppression conditions. These span values are equivalent to the ones described for information presented in other sensory modalities (e.g., Miller, 1956), also, the better performance in reconstruction of order than in immediate serial recall tasks is also congruent with studies on other sensory modalities (e.g., Whiteman et al., 1994). The main conclusion of these experiments are that articulatory suppression impairs the recall of haptic information in immediate serial recall, but is not so relevant when participants can perform a span task that does not require verbal retrieval of information, like in reconstruction of order tasks.

Reconstruction of order tasks have been considered as *pure* measures of order memory (e.g., Whiteman et al., 1994), however, Neath (1997) has shown that other type of information about the stimuli is encoded during reconstruction of order tasks and can affect the participant's performance. In our studies, one can assume that verbal encoding of the objects (or object naming) is an almost automatic task for common objects, although not bringing relevant inputs into the reconstruction of order task, since all participants needed to remember was the order of the object; but also, as been mentioned previously, verbal encoding is relevant even for uncommon object's processing (e.g. Lacey & Campbell, 2006). The lesser extent to which articulatory suppression impaired results in Experiment 2 can be understood considering the lack of relevance of naming in the retrieval phase.

Simultaneously, the minor impact of articulatory suppression in reconstruction of order can be understood attending to the fact that during stimuli exploration, the participants were able to access other non-verbal properties of the stimuli, namely tactual cues. During haptic exploration the participants were particularly sensitive to tactile features that could differentiate the objects (e.g., temperature, texture, weight) since it was the only form of contact with the stimuli, and these properties could have been retrieved during the test phase, allowing a better discrimination of the stimuli and facilitating the order responses.

According to the participants' errors analysis, there seems to be a facilitation effect of familiarity, with common objects presenting less errors than uncommon objects, confirming the previously reported connections between long-term and working memory in short-term tasks (e.g. Saint-Aubin & Poirer, 1999).

Likewise, these data suggest that participants were processing the stimuli attending to more detail than just the position in which they were being presented (Neath, 1997).

The number of items that were recalled through after a haptic exploration was very similar to the number of items recalled in other sensory modalities, and revealed a larger span than the one estimated with tactile location experiments (e.g. Gallace et al., 2008), showing that the type of stimuli and the type of exploration task is relevant for the estimation of tactual spans.

The present work allowed a new perspective on haptic span tasks, focusing on span for everyday objects in active touch conditions. Future work will focus in broadening these procedures to free recall conditions as well, possibly allowing a deeper study of the serial recall haptic curve plots, contributing to clarify the processes involved in haptic short-term and working memory.

REFERENCES

Atkinson, R., & Shiffrin, R. (1968). Human memory: A proposed system and its control processes. In K. Spence (Ed.), *The psychology of learning and motivation: advances in research and theory* (Vol. 2, pp. 89–195). New York: Academic Press

Baddeley, A.D., & Hitch, G.J. (1974). Working Memory. In G. Bower (Ed.), *The psychology of learning and motivation* (pp. 47–89). New York: Academic Press.

Baddeley, A.D., Thomson, N., & Buchanan, M. (1975). Word Length and Structure of Short-Term-Memory. *Journal of Verbal Learning and Verbal Behavior*, *14*(6), 575–589.

Bhatarah, P., Ward, G., Smith, J., & Hayes, L. (2009). Examining the relationship between free recall and immediate serial recall: Similar patterns of rehearsal and similar effects of word length, presentation rate, and articulatory suppression. *Memory & Cognition*, *37*(5), 689–713. doi:10.3758/MC.37.5.689

Bushnell, E.W., & Baxt, C. (1990). Children's Haptic and Cross-Modal Recognition With Familiar and Unfamiliar Objects. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(6), 1867–1881.

Conrad, R., & Hull, A. (1968). Input Modality and Serial Position Curve in Short-Term Memory. *Psychonomic Science*, *10*(4), 135-136.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, *24*(1), 87–185.

Craddock, M., & Lawson, R. (2009). The effects of size changes on haptic object recognition *Attention, Perception, & Psychophysics*, *71*(4), 910–923. doi:10.3758/APP.71.4.910

Crowder, R.G. (1976). Principles of learning and memory. Oxford: Lawrence Erlbaum

Fernandes, A.M. & Albuquerque, P.B. (submitted a). Haptic recognition of common objects: The effects of interference at encoding.

Fernandes, A.M. & Albuquerque, P.B. (submitted b). Recognizing uncommon objects by touch: effects of interference.

Gallace, A., Tan, H.Z., Haggard, P., & Spence, C. (2008). Short term memory for tactile stimuli. *Brain Research*, *1190*, 132–142. doi:10.1016/j.brainres.2007.11.014

Gilson, E.Q., & Baddeley, A.D. (1969). Tactile short-term memory. *Quarterly Journal of Experimental Psychology*, *21*(2), 180–184.

Kaas, A., Stoeckel, M., & Goebel, R. (2008). The neural bases of haptic working memory. In M. Grunwald (Ed.), *Human haptic perception: Basics and applications* (pp. 113–129). Basel: Birkhäuser.

Kiphart, M.J., Auday, B.C., & Cross, H.A. (1988). Short-term haptic memory for three-dimensional objects. *Perceptual and motor skills*, *66*(1), 79–91.

Klatzky, R.L., & Lederman, S.J. (2003). The Haptic Identification of Everyday Life Objects. In Y. Hatwell, A. Streri, & E. Gentaz (Eds.), *Touching for Knowing*. Philadelphia: John Benjamins Publishing Company.

Klatzky, R.L., Lederman, S.J., & Metzger, V. (1985). Identifying Objects by Touch - an Expert System. *Perception & Psychophysics*, *37*(4), 299–302.

Lacey, S., & Campbell, C. (2006). Mental representation in visual/haptic crossmodal memory: evidence from interference effects. *Quarterly Journal of Experimental Psychology*, *59*(2), 361–376. doi:10.1080/17470210500173232

Loomis, J., & Lederman, S.J. (1986). Tactual perception. In K. Boff, L. Kaufman, & J. Thomas (Eds.), *Handbook of perception and human performance*. New York: Organization.

Miles, C., & Borthwick, M. (1996). Tactile short-term memory revisited. *Memory*, *4*(6), 655–668.

Millar, S. (1972). Effects of interpolated tasks on latency and accuracy of intramodal and cross-modal shape recognition by children *Journal of Experimental Psychology*, *96*(1), 170–175. doi:10.1037/h0033546

Miller, G. (1956). The magical number seven, plus or minus two: some limits on our capacity for processing information. *Psychological Review, 101*(2), 343-352.

Nabeta, T., & Kusumi, T. (2008). Memory capacity for haptic common objects. *Perception, (37).* Abstracts Supplement 31st European Conference on Visual Perception.

Neath, I. (1997). Modality, concreteness, and set-size effects in a free reconstruction of order task *Memory & Cognition*, *25*(2), 256–263.

Oliveira, C. & Albuquerque, P.B. (February, 2010). Capacidade de Memória Operatória: Efeito da Interferência Proactiva. VII Simpósio Nacional de Investigação em Psicologia. Braga: Universidade do Minho

Oliveira, C. & Albuquerque, P.B (March, 2010). Capacidade de Memória Operatória: Efeito de uma tarefa de escuta dicótica. Poster apresentado no 5º Encontro da Associação Portuguesa de Psicologia Experimental. Braga: Universidade do Minho.

Purser, H., & Jarrold, C. (2010). Short- and long-term memory contributions to immediate serial recognition: evidence from serial position effects. *Quarterly Journal of Experimental Psychology*, *63*(4), 679–693. doi: 10.1080/17470210903067635

Saint-Aubin, J., & Poirier, M. (1999). The Influence of Long-term Memory Factors on Immediate Serial Recall: An Item and Order Analysis. *International Journal of Psychology*, *34*(5), 347–352. doi:10.1080/002075999399675

Sullivan, E., & Turvey, M. (1974). On the short-term retention of serial, tactile stimuli. *Memory & Cognition*, *2*(2), 600–606.

Tan, L., & Ward, G. (2008). Rehearsal in immediate serial recall. *Psychonomic Bulletin & Review*, *15*(3), 535–542. doi: 10.3758/PBR.15.3.535

Tulving, E. (1983). *Elements of episodic memory*. Oxford: Clarendon Press.

Watkins, M. & Watkins, O. (1974). A Tactile Suffix Effect. *Memory & Cognition*, *2*, 176–180.

Whiteman, H.L., Nairne, J.S., & Serra, M. (1994). Recognition and recall-like processes in the long-term reconstruction of order. *Memory*, *2*(3), 275–294.

Wijntjes, M.W.A., van Lienen, T., Verstijnen, I.M., & Kappers, A.M.L. (2008). Look what I have felt: unidentified haptic line drawings are identified after sketching. *Acta Psychologica*, *128*(2), 255–263. doi:10.1016/j.actpsy.2008.01.006

Unsworth, N., & Engle, R.W. (2007). On the division of short-term and working memory: An examination of simple and complex span and their relation to higher order abilities *Psychological Bulletin*, *133*(6), 1038–1066. doi: 10.1037/0033-2909.133.6.1038

PART III

CONCLUSION

Methodology and design are two defying topics within haptic and tactile research, specially when we aim to explore higher order processes as memory. The lack of studies on haptic memory in general and the contradictory data from passive tactile stimulation span tasks, challenge researchers in the definition of procedures to study memory in touch.

The present study suggested that it is possible to evaluate memory span in touch and implied that a short-term register in touch might be of a longer duration than the equivalent registers in auditory and visual modalities. Participants were able to correctly recall stimuli presented during a 60 second interval, presenting span values similar to the ones described for vision or audition. Reconstruction of order errors' revealed that stimuli familiarity can facilitate the tasks, leading to less errors. Performance in reconstruction of order was overall better than in immediate serial recall for common objects, resulted in a larger span, and revealed no effect of articulatory suppression, suggesting that participants might have been encoding and rehearsing the items with a non verbal strategy.

Future work should concentrate on the replication and generalisation of this results within the haptic modality by:

- Using within-subject designs to minimise between subject variability, for type of task (immediate serial recall and reconstruction of order tasks) and for stimuli type
- Evaluating performance in free recall haptic tasks or free reconstruction of order haptic tasks, as it might provide better insight as to primacy and recency effects in haptics;
- Shortening the haptic presentation times by one or two seconds and comparing the pattern of results, specially serial positions curves to understand what happens in shorter durations (e.g. Is there a tradeoff between number of items in the list and duration of the presentation of the list - can people recall the same amount of items regardless of the duration of list presentation);
- Directly comparing haptic span to visual and verbal span in optimal conditions for each modality (shortening presentations times for verbal and visual conditions).

O mínimo e o grande

Às coisas mínimas a ciência acrescenta coisas grandes.
Às coisas grandes a ciência acrescenta coisas pequenas.

Gonçalo M. Tavares, *em Breves notas sobre ciência*

PART IV

GENERAL CONCLUSIONS

The present work represents a first effort to systematically characterise haptic memory for everyday objects in free exploration conditions. In this thesis we presented two sets of studies regarding memory for objects perceived by touch. The first group of experiments focused on working memory interference paradigms, adapting the classical dual-task procedure to a haptic experiment, comparing the effects of motor, haptic, verbal and visuospatial interference at encoding with common and uncommon objects as stimuli. The second group of tasks emphasised haptic span tasks with everyday objects, evaluating the effects of articulatory suppression on haptic immediate serial recall and reconstruction of order tasks, and comparing performance between common and uncommon objects.

In the second part of this thesis a set of studies was presented, analysing haptic recognition in various interference tasks. These task were designed to explore the possibility of a tactile or haptic specificity in working memory, and to explore haptic encoding within Baddeley and Hitch's (1974; Baddeley, 2000) working memory theoretical model. As such, a verbal interference task was introduced to evaluate the contribution of the phonological loop, and a visuospatial task was presented to analyse the involvement of the visuospatial sketchpad. Considering the possibility of finding tactual specificity in working memory, we also tested the effects of a haptic interference task, and added a motor interference task to evaluate if the impact of the haptic task was tactile in nature (and dependent upon the intervention of higher order processes), or just a result of motor interference from the coordination of two different and simultaneous tasks.

An overview of the first set of studies, regarding interference tasks, showed that the participants' ability to recognise haptic stimuli was very high. With lists of 50 objects the participants were able to respond with rates well above chance, even in interference conditions, and regardless of the type of presented objects. Performance in no interference conditions was excellent for both common and uncommon objects, demonstrating the efficacy of our haptic system in resolving tasks similar to our everyday interaction with objects. Memory for haptically presented common objects was very robust and revealed that only haptic interference at encoding had a significant effect impairing haptic recognition. The experiment with uncommon objects showed that haptic recognition for these stimuli seemed to be more difficult than for the common objects, which was translated in worst haptic recognition when haptic, verbal or visuospatial interferences were presented at encoding, when compared to no interference conditions. However, in these experiments, it was possible to observe a tradeoff effect between the haptic interference task (evaluating paper samples) and the haptic exploration task (study phase of the objects), implying that these tasks were sharing cognitive resources.

A final comparison of performance for common and uncommon objects demonstrated a frequent effect in previous literature: common objects systematically presented better performance than uncommon objects, and in interference conditions, uncommon objects always presented more information loss when compared to no interference condition, than did the common objects. Overall, the previous experiments, suggest tactual specificity in memory processes.

The final group of experiments had an exploratory nature. We intended to conduct preliminary studies that would allow the improvement of the design, methods, and general understanding of haptic memory span for naturalistic stimuli, in free exploration conditions. We implemented adaptations of two central memory span paradigms, immediate serial recall and reconstruction of order tasks, attempting to adjust the presentation times to the particularities of haptic sensory modality, increasing both exploration and between stimuli intervals. Acknowledging the relevance of verbal encoding for the selected stimuli, we designed the experiments including an articulatory suppression condition, that allowed an estimation of the impact of verbal encoding and rehearsal in the retrieval of haptic information. The reconstruction of order task, unlike the immediate serial recall task, did not require the identification of the stimuli, and as such allowed the comparison of performance with highly familiar and identifiable objects (common objects) and unfamiliar and hardly identifiable objects (uncommon objects) and explored the respective performance patterns. Results showed that immediate serial recall for haptic common objects resulted in a span of five objects in single task condition and of four objects in articulatory suppression conditions. For reconstruction of order tasks, the span values were higher, with an average of one more item in each condition for both common and uncommon objects.

Summing the present results and attending to previous research in the areas of haptic perception, haptic memory and working memory, one can assume that there seems to be some evidence to argue in favour of a sensory specificity in memory, specifically, the need to assume that haptic information in perceived and maintained in memory through some modality-specific processes, and not only abstract, conceptual or amodal representations of stimuli. Likewise, the idea that haptic information is simply transformed in visuospatial information and encoded and retrieved as such, does not seem to find empirical support.

Future research on haptic memory must be interested in the adaptation of classical paradigms such as the dual-task paradigm and memory span tasks, as presented in this study, but always attending to the specific characteristics of haptic perception, considering exposition times, type of stimuli, type of exploration procedure, and even the type of participants' as central variables to access haptic processing.

This work constituted a first effort to systematically study human memory using an under explored sensory modality as a way to present stimuli. Results reveal that previous knowledge on memory, obtained through visual and auditory tasks, might not be generalised to all perceived information, and as such, might not correspond to the best available interpretation and comprehension of human memory. Research on higher order cognitive processes through touch is a developing area of knowledge in psychology, neurosciences and even technologic areas, promising a fast development in the next few years that will surely contribute to a finer comprehension of human cognition, specially human haptics.

REFERENCES

Baddeley, A.D. (2000). The episodic buffer: a new component of working memory *Trends in Cognitive Sciences*, *4*(11), 417–423.

Baddeley, A.D., & Hitch, G.J. (1974). Working Memory. In G. Bower (Ed.), *The psychology of learning and motivation* (pp. 47–89). New York: Academic Press.

> ***Instrumentos científicos***
>
> *Cada instrumento científico não é uma resposta em Forma e Função dos Mistérios do Mundo.*
> *Cada instrumento científico é uma resposta às necessidades de um investigador.*
>
> Gonçalo M. Tavares*, em Breves notas sobre ciência*

PART V

APPENDICES

Appendix A: Objects' lists

COMMON OBJECTS

Adhesive tape
Bath puff
Bracelet
Calculator
Candle
Cassette
Cellular phone
Cloth
Clothespin
Coffee cup
Comb
Contact lenses box
Cork
Cork screw
Corrector pen
Deodorant
Dish sponge
Doll
Drinking straw
Fork
French clip
Glass
Glasses case
Glue stick
Hair claw
Hairband
Hairbrush
Hammer
Hand cream container
Headphones
Highlighter
Hole puncher
Keychain
Knife
Lamp
Lantern
Lighter
Lipstick
Lollipop
Magnifying glass
Nail brush
Nail clippers
Nail polish
Notepad
Nutcracker
Pacifier
Painting brush
Pc mouse
Pen
Pencil
Pencil case
Penknife
Phone charger
Plastic glove
Pliers
Plush
Rasp
Rubber

Saucer

Scissors

Scouring pad

Screw

Screwdriver

Shaving brush

Shoe brush

Shoehorn

Small ball

Soap

Soap-dish

Spatula

Spoon

Spun yarn

Stapler

Staples remover

Strainer

Sunglasses

Swimming cap

Tea bag

Three way plug

Tissue pack

Toothbrush

Toothpaste

Tupperware

Tweezers

Umbrella

Wallet

Whistle

Wooden box

Wrench

Wristwatch

Yarn ball

Yogurt container

UNCOMMON OBJECTS

Badge

Calculator

Candle metal box

Carabiner

Card deck

Cartridge

Conch

Coral bath sponge

Decoration statue

Flash drive

Floppy disk box

Flower-shaped nail polish

Garbage shovel

Garlic peeler

Hand fan

Heart-shaped plastic box

Honey spoon

Horn

Large bracelet

Large pen

Lip gloss package

Massager

Medal

Metric tape

Miniaturized ashtray

Miniaturized boat

Miniaturized bucket

Miniaturized cake pan

Miniaturized ceramic hat

Miniaturized clay fruit bowl

Miniaturized duct tape dispenser

Miniaturized frying pan

Miniaturized helmet

Miniaturized jar

Miniaturized liquid soap package

Miniaturized milk pan

Miniaturized mop

Miniaturized perfume bottle

Miniaturized photo machine

Miniaturized plastic bathtub

Miniaturized plastic chair

Miniaturized plastic glass

Miniaturized plastic hairdresser

Miniaturized plastic handsaw

Miniaturized plastic knife

Miniaturized plastic tractor

Miniaturized portable ashtray

Miniaturized tank

MP3 player

Pan coaster

Paperweight

Photo holder

Plastic bracelet

Plastic chili

Plastic miniaturized basket

Plastic miniaturized maize ear

Plastic miniaturized spoon

Plastic miniaturized toilet

Plastic onion

Plastic pen box

Plastic pliers

Plastic rasp

Plastic robot toy

Plastic screw

Plastic Screw driver

Plastic strawberry

Plastic tomato

Plastic tube

Plastic walnut

Plastic wrench

Pot

Rattan decoration ball

Rounded remote control

Small hourglass

Small snow globe

Soap dish

Stapler remover

Toy mobile phone

Wall hanger

Wooden flute

Wooden hand mirror

Wooden plaques toy

Wooden spatula

Appendix B: Visuospatial Interference Stimuli

The visuospatial interference task had to be a task sufficiently demanding to force participants to concentrate on it while touching the objects. In some pilot studies we experimented a few other tasks that were proved to be too easy to require permanent concentration. One of these tasks was the presentation of dynamic visual noise while participants touched the objects. Although previous interference studies (Lacey & Campbell, 2006) had argued that dynamic visual noise would be disturbing to a haptic task, we found that the three participants in the pilot study did not suffer any kind of interference from the task and reported they felt no additional difficulty in performing the haptic task. A second pilot study using a tracking paradigm, revealed that following moving dots along the screen did not affect the ability to explore and later recognise touched objects.

Due to the robust results in single task haptic recognition, with recognition rates of nearly 100%, we decided to advance to a paradigm using difficult interference tasks, in order to analyse participants' performance in demanding conditions. We used Shepard and Metzler's (1971) three dimensional abstract stimuli and evaluated what was the rotation that participants were able to correctly perform in a three second interval in dual-task conditions. According to the original work, in three seconds and single task condition, participants would be able to perform a rotation of about 100º (Shepard & Metzler, 1971), but we found that in dual task conditions this ability was impaired, as is shown below.

METHOD

Participants

Four psychology graduate students participated in these pilot studies (mean age of 27.0, SD = 4.0), all female.

Materials and Stimuli

A wooden box with two openings (one facing the participant, covered with a white cloth to prevent visual contact with the haptic stimuli, and another facing the experimenter), and headphones producing white noise were used during the experiment.

A set of stimuli with different rotations was selected from Shepard and Metzler (1971) stimuli. One group of stimuli had a rotation of 80º, other a rotation of 40º and a third one a rotation of 20º. The visuospatial task consisted in evaluating stimuli in a "same/different" paradigm. "Same" pairs referred to the same object presented in different rotation (80º, 40º or 20º, according to the group) and "different" pairs were composed by mirror images of the same object with a rotation of 80º, 40º or 20º, respectively. For the simultaneous haptic exploration task, a set of 20 common objects was selected from a pool of 92 common objects (see Appendix 1).

Procedure

Participants had to perform a same/different task regarding the rotations of each stimuli pair. Each pair was presented simultaneously on the screen for three seconds. When the stimuli disappeared, participants had to provide an answer to the question “Were the two images representations of the same object in different rotations?”. Participants performed this visuospatial task simultaneously with an haptic task that consisted in freely exploring a common object whit their non-dominant hand while the visuospatial stimuli were presented on the screen. Each participant evaluated 20 stimuli pairs (10 “same” pairs). At the end of this phase, participants had to perform a haptic recognition task for the touched objects (20 objects, 10 presented). There were two participants in the 40º rotation condition and one participant in each of the other conditions.

RESULTS

In dual task conditions, a 80º rotation in the stimuli produced a correct answer rate of about .30; a 20º rotation revealed about .80 performance rate and a 40º rotation implied results of .60. Performance in the haptic task was very high (about 1) for every condition, revealing that the visuospatial task seemed not to be disrupting haptic performance. Figure 11 shows the values for the visuospatial and haptic task in each condition.

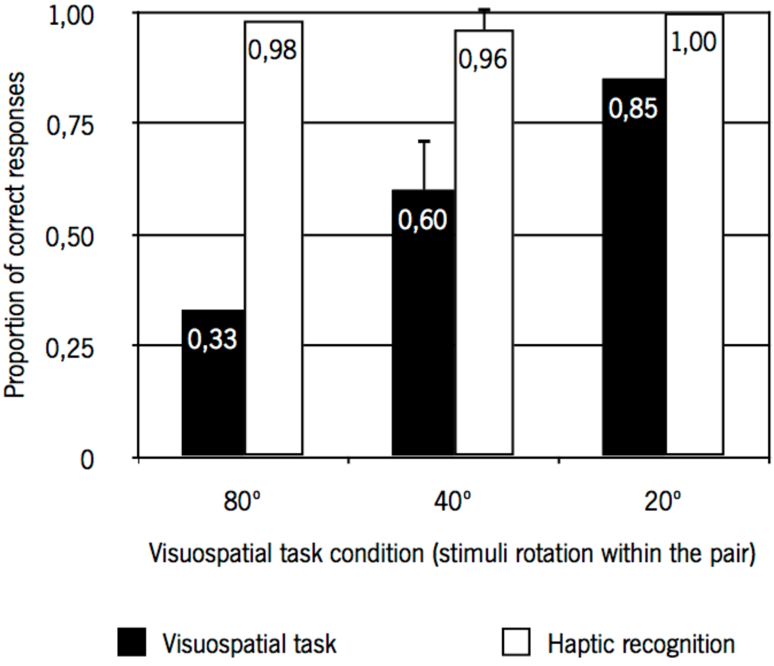

Figure 11: Correct responses in visuospatial task and haptic recognition

CONCLUSION

In a procedure with 20 objects, haptic memory for previously touched objects was not affected by a demanding visuospatial task at encoding, in any of the presented rotations.

For the visuospatial task, a 80º rotation in a three seconds presentation time resulted in a very low correct response rate in dual-task conditions. On the other hand, this task, performed with a 20º rotation of the figures seem to present no challenge to the participant, resulting in a high correct response rate. According to the present results, the 40º rotation rate of the figures in the visuospatial tasks seems to be the option that allowed participants to perform the task with a reasonable accuracy and simultaneously kept the task demanding.

REFERENCES

Lacey, S., & Campbell, C. (2006). Mental representation in visual/haptic crossmodal memory: evidence from interference effects. *Quarterly Journal of Experimental Psychology*, *59*(2), 361–376. doi:10.1080/17470210500173232

Shepard, R.N., & Metzler, J. (1971). Mental Rotation of Three-Dimensional Objects. *Science*, *171*(3972), 701–703. doi: 10.1126/science.171.3972.701

Appendix C: Haptic Interference Stimuli

An experiment was conducted to evaluate the stimuli used in the haptic interference task. This task consisted in the evaluation of paper sample pairs. Each stimulus was created pseudo-randomly, matching the pairs and then attaching the respective available paper samples in a 14.8 cm x 21.0 cm (A5 size) cardboard. Each sample was cut with a dimension of 7.4 cm x 21.0 cm and glued longitudinally to the cardboard. A sponge strap with 1.0 cm x 21.0 cm was placed in the middle of the cardboard, over the paper samples, dividing the cardboard in half and separating the two paper samples. Paper tape was used to protect the margins of the cardboard.

METHOD

Participants

Eleven volunteers (M = 28.9, DP = 5.8, two male) that did not participate in the haptic interference condition.

Materials

For this experiment we used 110 stimuli pairs (52 “same” pairs). A wooden box, with the front covered by a white cloth prevented participants from seeing the stimuli during the task. The box was divided internally by a white cardboard, so that participants could only touch the samples with one of their hands.

Table 6: Types of paper used to construct the stimuli in the haptic interference task

1	Shiny notebook cover page	**19**	Corrugated cardboard	**37**	Smooth cardboard
2	Lustre paper	**20**	Corrugated cardboard inverted	**38**	Strong newspaper paper
3	Newspaper printed paper	**21**	Napkin paper inverted	**39**	Booklet cover smooth paper
4	Vegetal paper	**22**	Strong ruled paper	**40**	Magazine paper 3
5	Celofane paper	**23**	Plastic paper	**41**	Napkin paper
6	Metallic paper	**24**	Fragile wrap paper inverted	**42**	Fragile magazine paper
7	Thin cardboard	**25**	Colorful strong paper	**43**	Recycled fragile paper
8	Strong and rough white paper	**26**	Recycled wrap paper	**44**	Smooth magazine paper
9	Magazine cover paper 1	**27**	Magazine paper 2	**45**	Strong magazine paper
10	Strong printed notebook paper	**28**	Notebook paper	**46**	Magazine cover paper 2
11	Recycled paper with rafia	**29**	Recycled ruled paper	**47**	Photo paper
12	Smooth and strong shiny paper	**30**	Recycled ruled paper inversed	**48**	Photo paper inversed
13	Recycled smooth paper	**31**	Colorful paper	**49**	Recycled envelope paper
14	White paper (regular)	**32**	Strong notebook paper inversed	**50**	Recycled envelope paper inverted
15	Recycled harsh paper	**33**	Strong white paper	**51**	Kitchen paper
16	Recycled smooth paper	**34**	Recycled ruled paper 2	**52**	White printed paper
17	Booklet paper inverted	**35**	Wrap paper inversed		
18	Strong wrap paper	**36**	Cardboard		

A computer runing Superlab presented the sound cues that determined the time interval for haptic exploration of each paper pair, through a “start” and a “stop” sound. A set of 52 paper types was used, table 6 shows each paper type associated with a number. In the pair designation (Table 7), each paper sample is identified by its respective number.

During the task, participants wore headphones transmitting white noise to mask any exploration sounds.

Table 7: Composition of the “different” paper sample pairs

1 - 2
1 - 11
2 - 3
2 - 4
2 - 5
2 - 6
2 - 7
2 - 8
2 - 10
2 - 13
2 - 14
3 - 4
3 - 5
3 - 6
3 - 7
3 - 8
3 - 12
3 - 13
4 - 5
4 - 6
4 - 7
4 - 8
4 - 11
4 - 13
5 - 6
5 - 7
5 - 8
5 - 10
5 - 13
6 - 7
6 - 8
6 - 10
6 - 13
6 - 14
6 - 15
7 - 8
7 - 10
7 - 13
7 - 16
7 - 25
8 - 9
8 - 10
8 - 12
8 - 13
8 - 25
9 - 10
10 - 12
10 - 13
11 - 12
13 - 14
14 - 15
15 - 16
29 - 30

Procedure

Participants sat on a chair and placed their hands inside the wooden box, one hand in each side of the cardboard division, and touched the samples with their dominant hand. At the beginning of the experiment, participants were asked to keep their non-dominant hand in a comfortable position, and to place their dominant hand with its back touching the box’s ceiling. Through headphones, participants heard “start” and “stop” sounds that limited exploration time. When the “start” signal sounded, participants had to lower their dominant hand until they reached the paper sample pair that was placed in the bottom of the box. Once in contact with the paper sample, participants had to rub, simultaneously, the two paper samples using their fingers. A “stop” signal sounded after three seconds and at this time participants had to rise their hand to the top of the box again. This procedure was followed for each of the evaluated paper samples. Before the task began, participants saw a paper sample pair, and it was explained that the sponge strap was a divider of the two samples and was present in every stimuli to guide exploration. Afterwards, six training trials were performed so that participants could test the procedure and get comfortable with the timing for exploration, and task difficulty. Each participant evaluated a randomised set of 50 paper samples (25 “same” pairs). In this task participants had to evaluate how similar each paper pair was in a 10 point Likert scale, (where 1 was “completely different” and 10 was “the same sample”).

RESULTS

The average evaluation of each stimuli type is shown in Table 8.

Table 8: Mean values of haptic similarity for each pair (“different” stimuli are marked with a “D” and “same”stimuli are marked with a “S”)

	Mean	SD		Mean	SD		Mean	SD
D 1 11	2,0	1.1	**D 5 7**	5.3	2.6	**S 25**	9.7	0.8
D 1 2	6.4	3,0	**D 5 8**	2.7	2.9	**S 26**	8.8	1.8
D 10 12	6.4	2.1	**D 6 10**	4.4	3.2	**S 27**	9.6	0.5
D 10 13	8.8	1.6	**D 6 13**	2.6	2.3	**S 28**	9,0	1.2
D 11 12	5.8	2.8	**D 6 14**	2.3	3,0	**S 29**	6.3	2.6
D 11 4	4,0	0,0	**D 6 15**	1,0	0,0	**S 3**	6.9	2.5
D 13 14	7.6	1.9	**D 6 7**	3.5	3,0	**S 31**	9,0	1,0
D 14 15	3.5	4.4	**D 6 8**	1.3	0.5	**S 32**	9.4	0.9
D 15 16	1.6	0.5	**D 7 10**	8,0	1.8	**S 33**	9,0	0.7
D 2 10	3.6	3,0	**D 7 13**	8.3	1.4	**S 34**	7.6	2.7
D 2 13	4,0	2.4	**D 7 16**	8.5	0.8	**S 35**	8,0	1.9
D 2 14	5.2	2.6	**D 7 25**	6.4	2.2	**S 36**	8.6	1.7
D 2 3	4,0	2.8	**D 7 8**	5.5	2.5	**S 37**	9.5	0.8
D 2 4	4,0	2.2	**D 8 10**	6.3	2.1	**S 38**	8.7	1.8
D 2 5	6,0	3.4	**D 8 12**	8.8	2.2	**S 39**	7.7	2.7
D 2 6	5.6	3.8	**D 8 13**	2.8	1.8	**S 4**	8.8	1,0
D 2 7	6.6	1.8	**D 8 16**	9,0	0.8	**S 40**	9.8	0.4
D 2 8	5.3	2.4	**D 8 25**	4.5	3.4	**S 41**	9.9	0.4
D 29 30	5.6	3.6	**D 8 9**	2.3	1.4	**S 42**	8.3	2.7
D 3 10	5.5	6.4	**D 9 10**	3.2	2.3	**S 43**	9.5	0.8
D 3 12	4,0	2,0	**S 1**	9.2	1.3	**S 44**	9,0	1.3
D 3 13	8.3	1.6	**S 10**	8.2	2.9	**S 45**	7.8	0.5
D 3 4	7,0	1.2	**S 11**	8,0	1.5	**S 46**	8.7	1.2
D 3 5	3.3	2.6	**S 12**	8.4	3.6	**S 47**	8.5	2.4
D 3 6	1.5	0.6	**S 13**	8.4	2.1	**S 48**	8.6	1.1
D 3 7	6.3	2.9	**S 15**	8.3	2.9	**S 49**	8.9	1.7
D 3 8	9.6	0.5	**S 16**	7.3	2.1	**S 5**	10,0	0,0
D 4 11	9,0	1.3	**S 17**	9.6	0.9	**S 50**	7.8	2.5
D 4 13	7.3	2.3	**S 18**	8,0	2.8	**S 51**	9.6	0.9
D 4 5	1.6	1.3	**S 19**	9.5	1.2	**S 52**	9.6	0.8
D 4 6	1.8	1.3	**S 2**	8,0	2.1	**S 53**	9.3	0.8
D 4 7	7,0	1.4	**S 20**	8.6	2.3	**S 6**	9.4	0.9
D 4 8	6,0	3.5	**S 21**	9.2	0.4	**S 7**	9.3	0.8
D 5 10	4.2	4.4	**S 22**	8.9	0.9	**S 8**	9.3	0.8
D 5 13	3.2	3.5	**S 23**	8.2	0.8	**S 9**	9.8	0.4
D 5 6	9,0	1.5	**S 24**	9.7	0.5	**S14**	8.5	2.3

“Different” pairs have a clearly lower evaluation than “same” pairs, with an average of 5.2 (*SD* = 3.2) and 8.7 (*SD* = 1.8) respectively, in a 10 point Likert scale, *t* (10) = 8.29, *p* < .001, *r* = .934. Mean scores for each pair are illustrated in table y. It is possible to see that 26 of the “different” samples present a score below five in the scale, revealing that participants’ found these pairs relatively easy to discriminate. A set of four pairs (D3.8,D4.11, D5.6, D8.16) had a mean score equal or superior to nine and as such these pairs were considered the most difficult pairs to discriminate. Although for both types of pairs, a maximum rate of 10 and a minimum rate of 1 was found, descriptive analysis shows that the mode for “different” pairs was 1 and for “same” pairs was 10.

CONCLUSION

Participants showed a good discrimination ability for the totality of the presented pairs. All the “same” pairs showed a mean score over 6 and .46 of “different” pairs reveal a score below five. Only a proportion of .07 of “different” pairs exhibit an average score equal or above nine.

Appendix D: Verbal Interference Stimuli

For the verbal interference task we decided to select pseudowords instead of real-words. Pseudowords present two main advantages: first, not being real words, they do not belong nor relate to any object category and, as such, are independent of the haptic stimuli we presented; second, pseudowords have an abstract nature that makes them more comparable with the stimuli we used in haptic and visuospatial interference tasks.

In our pilot studies with these pseudowords we wanted to evaluate which type of pairs participants would be able to read out loud and respond to in a three second interval. The pseudowords for all experiments were randomly selected from Pureza (2009).

EXPERIMENTS

General design

Participants sat in a chair in front of a table where the experimental set up was presented. The set up consisted of a wooden box with the front covered by a white cloth. On top of the box there was a computer screen where the verbal stimuli were presented. During the experiment, participants wore headphones that produced white noise. The verbal task consisted in presenting in a computer screen pseudoword pairs that had to be read out loud by the participants in a three seconds presentation time. After that time, stimuli would disappear from the screen and participants had to provide a verbal answer to a question about the presented pseudowords pair, in a "same/different" paradigm.

EXPERIMENT 1

Participants

Two participants took part in this experiment (two females with ages of 17 and 18 years, undergraduate students of psychology).

Materials

Stimuli set was composed by three and four syllable pseudowords. Each pair was composed by two pseudowords, presented simultaneously at the centre of the screen: "same" pairs had two pseudowords with the same number of syllables (either three or four) and "different" pair were composed by a three syllable and a four syllable pseudo-word.

Procedure

Once the stimuli disappeared, participants had to provide an answer to the question: “Did the two words had the same number of syllables?”.

EXPERIMENT 2

Participants

Two participants took part in this experiment (two females, 18 years, undergraduate students of psychology).

Materials

Stimuli set was composed by four syllables pseudowords. Each pair was composed by two pseudowords, presented simultaneously at the centre of the screen: “same” pairs were composed by four syllable pseudowords with one syllable in common and “different” pairs were composed by four syllable pseudowords with no common syllable.

Procedure

Once the stimuli disappeared, participants had to provide an answer to the question: “Did the two words had at least one common syllable?”.

EXPERIMENT 3

Participants

Three participants took part in this experiment (three females, one with 17 years and the other two with 18 years, undergraduate students of psychology).

Materials

Three syllable pseudowords were selected for this experiment. “Same” pair consisted of three syllable pseudowords with one common syllable and “different” pairs consisted of three syllable pseudowords with no common syllable.

Procedure

Once the stimuli disappeared, participants had to provide an answer to the question: “Did the two words had the same number of syllables?”.

EXPERIMENT 4

Participants

Three participants took part in this experiment (one male, 24 years, graduate student of psychology, and two females with 18 years, undergraduate student of biomedical engineering, and 32 years, graduate student of psychology).

Materials

For this task, “different” stimuli pairs were composed by exchanging two letters within the pseudowords between syllables. In half the pairs a vowel was exchanged and in the other half a consonant was changed. Syllable order within the pseudowords was randomized for both “same” and “different” pairs. As such, “same” pairs were composed by three syllable pseudowords with the same syllables in different order and “different” pairs were composed by three syllable pseudowords with two letters exchanged with the word and syllables in random order.

Procedure

Once the stimuli disappeared, participants had to provide an answer to the question: “Did the two words had exactly the same syllables?”.

RESULTS

Figure 12 shows performance in the four verbal tasks we tested. Experiment 1, that consisted in the comparison between three and four syllable pseudowords reveal a ceiling effect, with participants correctly identifying a high rate of the presented pairs. In experiment 2, four syllable pseudowords pairs revealed the lowest performance rate. In this task it was possible to observe that participants were not able to read both four syllables pseudowords in the presented three seconds interval, and this had a clear effect in participants performance. In experiment 3, where participants had to compare three syllable pseudowords, performance was high, showing that verbal tasks difficulty had to be increased. Only in experiment 4, with a structural change in the stimuli constructed, we were able to obtain a task difficult enough to be equivalent to the haptic and visuospatial tasks, and, at the same time, a task that participants were able to perform in the desirable time interval of three seconds.

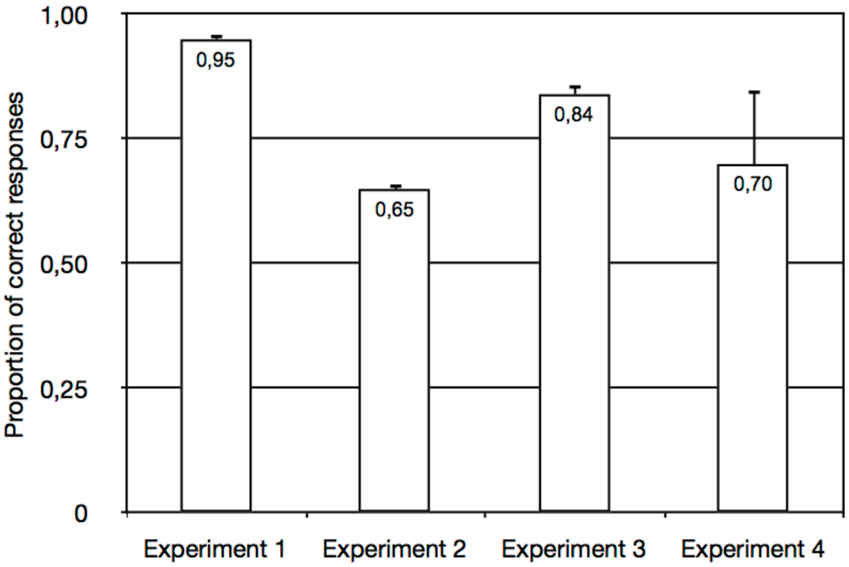

Figure 12: Performance in each of the four verbal interference tasks

GENERAL CONCLUSION

Participants were able to have an equivalent level of performance in the verbal tasks and visuospatial and haptic tasks when they were required to evaluate trisyllable pseudowords with only one different letter. All the verbal task options we experimented revealed that participants had no difficulty in performing verbal tasks and the error rate only became visible when we transformed the task to match the task demands with visuospatial and haptic tasks. Attending to these results, the stimuli from experiment 4 were selected as the best verbal interference tasks to present in haptic recognition.

REFERENCES

Pureza, R. (2009). *Priming fonológico na recuperação de estados Tip-of-the-Tongue: O papel da posição e da extensão silábicas*. Unpubliched master´s thesis, University of Minho, Braga, Portugal

Appendix E: Objects' Familiarity

With this experiment, we intended to analyse object familiarity to understand how this variable could affect our results in haptic tasks. Also, familiarity evaluations allowed us to select specific objects as stimuli for the span tasks.

Participants

Thirty volunteers (*M* = 23.2, *SD* = 2.3), undergraduate and graduate students participated in this experiment.

Materials and stimuli

Participants had to touch the objects by placing their hands inside a wooden box with the front covered by a white cloth, which prevented visual contact with the objects. Participants touched each object with their non-dominant hand for three seconds. A total of 175 everyday objects was used (92 common objects and 83 uncommon objects). Participants wore headphones during the experiment. The headphones transmitted white noise and the cues that determined the beginning and ending of each exploration period.

Procedure

Participants' had to rate each touched object according to its familiarity in a five point Likert scale, where one was described as "an object that you never used or use about once a year" and five was described as "an object that you use everyday or almost everyday". Besides the evaluation in the scale, participants were able to report that they did not knew the object, in which case they did no perform the familiarity evaluation. Each participant touched a set of 100 objects (50 common and 50 uncommon) chosen randomly from the pool of 175 objects. The objects were presented in random order for three seconds each. After the presentation time, participants had to provide an answer or report that they did not knew the object.

RESULTS

Overall results show a clear distinction between common and uncommon objects, t (29) = 13.9, $p < .001$, $r = .932$, with a mean familiarity of 3.5 (*SD* = 0.5) and of 2.5 (*SD* = 0.6) respectively. Figure 13 shows the mean values for familiarity in common and uncommon objects. The rate of unknown objects is superior in uncommon (*M* = 0.24, *SD* = 0.08) than in common (*M* = 0.06, *SD* = 0.04) objects, t (29) = −14.09, $p < .001$, $r = .934$.

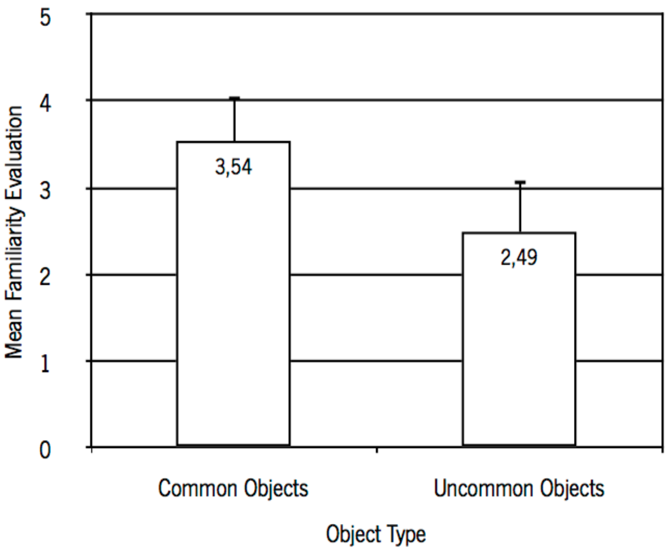

Figure 13: Mean values of familiarity for common and uncommon objects

Table 9 and Table 10 show, respectively, the mean familiarity values for common and uncommon objects, discriminating the values for each object in the sets.

Table 9: Mean familiarity values for common objects

	Mean	SD		Mean	SD		Mean	SD
Adhesive tape	3,87	0,99	**Hole puncher**	4,14	0,95	**Screwdriver**	2,54	1,39
Bath puff	4,14	1,29	**Keychain**	4,29	1,27	**Shaving brush**	2,40	1,80
Bracelet	3,64	1,28	**Knife**	5,00	0,00	**Shoe brush**	3,14	1,51
Calculator	3,67	1,18	**Lamp**	3,33	1,61	**Shoehorn**	2,21	1,72
Candle	2,50	1,73	**Lantern**	2,40	0,97	**Small ball**	3,33	1,40
Cassette	2,00	1,47	**Lighter**	2,64	1,57	**Soap**	3,55	1,57
Cellular phone	4,10	1,37	**Lipstick**	3,38	1,30	**Soap-dish**	3,00	0,76
Cloth	3,86	1,03	**Lollipop**	3,43	1,34	**Spatula**	2,17	1,64
Clothespin	4,43	0,94	**Magnifying glass**	2,64	1,55	**Spoon**	4,77	0,60
Coffee cup	4,67	0,82	**Nail brush**	3,07	1,44	**Spun yarn**	2,50	1,31
Comb	4,80	0,77	**Nail clippers**	4,15	0,80	**Stapler**	3,86	1,17
Contact lenses box	3,00	1,85	**Nail polish**	2,14	1,21	**Staples remover**	3,21	1,19
Cork	2,50	1,35	**Notepad**	4,36	0,74	**Strainer**	3,67	1,35
Cork screw	3,14	1,29	**Nutcracker**	2,46	1,20	**Sunglasses**	3,79	1,37
Corrector pen	4,00	1,35	**Pacifier**	2,29	1,73	**Swimming cap**	3,38	1,12
Deodorant	4,82	0,40	**Painting brush**	2,47	1,51	**Tea bag**	2,78	1,56
Dish sponge	4,47	0,99	**Pc mouse**	4,93	0,26	**Three way plug**	3,22	1,30
Drinking straw	3,62	1,04	**Pen**	4,43	0,94	**Tissue pack**	4,43	0,94
Doll	2,45	1,44	**Pencil**	4,36	1,28	**Toothbrush**	4,71	1,07
Fork	5,00	0,00	**Pencil case**	3,25	1,29	**Toothpaste**	4,67	0,71
French clip	2,62	1,85	**Penknife**	2,25	1,06	**Tupperware**	2,57	1,62
Glass	4,87	0,52	**Phone charger**	4,45	0,82	**Tweezers**	3,73	1,39
Glasses case	3,29	1,27	**Plastic glove**	3,23	1,54	**Umbrella**	3,25	0,62
Glue stick	3,11	1,36	**Pliers**	2,62	1,45	**Wallet**	4,57	0,85
Hair claw	2,92	1,08	**Plush**	2,62	1,50	**Whistle**	2,17	1,19
Hairband	2,91	1,51	**Rasp**	2,86	1,51	**Wooden box**	2,69	1,32
Hairbrush	4,93	0,26	**Rubber**	4,57	0,76	**Wrench**	2,46	1,66
Hammer	2,09	1,30	**Saucer**	4,93	0,27	**Wristwatch**	4,46	0,97
Headphones	4,00	1,41	**Scissors**	4,20	0,77	**Yarn ball**	2,40	1,55
Hand cream container	4,60	0,74	**Scouring pad**	3,73	1,49	**Yogurt container**	3,64	1,50
Highlighter	3,82	1,47	**Screw**	2,60	1,59			

Table 10: Mean familiarity values for uncommon objects

	M	SD		M	SD		M	SD
Badge	2,36	1,36	**Miniaturized ceramic hat**	1,67	0,58	**Plastic miniaturized spoon**	2,69	1,55
Calculator	1,33	0,58	**Miniaturized clay fruit bowl**	2,22	1,72	**Plastic miniaturized toilet**	2,00	1,73
Candle metal box	3,08	1,12	**Miniaturized duct tape dispenser**	2,50	1,91	**Plastic onion**	2,93	1,69
Carabiner	2,07	1,38	**Miniaturized frying pan**	3,33	1,44	**Plastic pen box**	2,00	0,00
Card deck	2,60	1,26	**Miniaturized helmet**	1,75	1,04	**Plastic pliers**	2,57	1,51
Cartridge	1,50	1,00	**Miniaturized jar**	2,17	0,75	**Plastic rasp**	2,30	1,64
Conch	2,64	1,69	**Miniaturized liquid soap package**	2,50	1,91	**Plastic robot toy**	1,25	0,50
Coral bath sponge	2,33	1,15	**Miniaturized milk pan**	3,92	1,61	**Plastic screw**	2,38	1,19
Decoration statue	1,00	0,00	**Miniaturized mop**	2,89	1,27	**Plastic Screw driver**	2,00	0,00
Flash drive	2,00	1,22	**Miniaturized perfume bottle**	1,50	0,71	**Plastic strawberry**	2,13	1,46
Floppy disk box	2,67	1,37	**Miniaturized photo machine**	1,33	0,58	**Plastic tomato**	3,25	1,36
Flower-shaped nail polish	2,00	1,73	**Miniaturized plastic bathtub**	1,75	0,50	**Plastic tube**	1,50	0,71
Garbage shovel	2,33	1,00	**Miniaturized plastic chair**	3,67	1,53	**Plastic walnut**	1,91	1,14
Garlic peeler	1,25	0,50	**Miniaturized plastic glass**	2,13	1,46	**Plastic wrench**	1,67	1,63
Hand fan	2,00	1,41	**Miniaturized plastic hairdresser**	1,50	0,71	**Pot**	1,88	1,13
Heart-shaped plastic box	2,00	0,00	**Miniaturized plastic handsaw**	3,00	1,07	**Rattan decoration ball**	1,83	1,27
Honey spoon	1,75	0,71	**Miniaturized plastic knife**	2,33	2,31	**Rounded remote control**	4,15	1,34
Horn	1,77	1,48	**Miniaturized plastic tractor**	2,29	1,59	**Small hourglass**	1,67	0,82
Large bracelet	3,57	1,28	**Miniaturized portable ashtray**	1,00	0,00	**Small snow globe**	1,50	1,00
Large pen	4,13	0,99	**Miniaturized tank**	2,20	1,64	**Soap dish**	2,80	0,84
Lip gloss package	1,80	1,30	**MP3 player**	2,80	1,79	**Stapler remover**	1,67	1,03
Massager	1,69	1,32	**Pan coaster**	2,67	1,41	**Toy mobile phone**	3,67	1,63
Medal	3,67	1,75	**Paperweight**	1,33	0,52	**Wall hanger**	3,11	1,76
Metric tape	1,83	0,98	**Photo holder**	4,00	1,00	**Wooden flute**	3,67	1,15
Miniaturized ashtray	2,71	1,54	**Plastic bracelet**	2,38	0,92	**Wooden hand mirror**	4,10	0,99
Miniaturized boat	1,00	0,00	**Plastic chili**	2,17	1,60	**Wooden plaques toy**	1,67	1,15
Miniaturized bucket	3,00	1,83	**Plastic miniaturized basket**	2,33	1,51	**Wooden spatula**	3,77	1,24
Miniaturized cake pan	3,09	1,38	**Plastic miniaturized maize ear**	2,33	1,58			

CONCLUSIONS

Common objects were, as expected, evaluated as more familiar than uncommon objects. Also, uncommon objects present lower identification rates than common objects.

Within common objects, we can observe that there are 31 objects the are always rated as “everyday use objects” (mean evaluation equal or superior to four), while for uncommon objects, only four are included in this category. Contrary, for “never used objects”, one can find three uncommon objects systematically evaluated with 1, but none common objects were fitted in this category.

Appendix F: Objects' Identification

This preliminary experiment was conducted to evaluate participants' ability to name each of the stimuli we intended to use on our memory tasks. The naming task was designed using the same overall procedure of memory tasks - participants always touched the objects with their non-dominant hand and without visual contact for three seconds each and with a five second inter-stimulus interval.

METHOD

Participants

Thirty volunteers, undergraduate, graduate and former students of University of Minho (*M* = 26.0, *SD* = 1.7, 11 male) participated in this experiment.

Materials

Participants touched a set of 50 objects, randomly chosen from a pool of 92 for common objects or from a pool of 83 for uncommon objects. All objects were small enough to allow exploration with only one hand and enabled silent manipulation. Participants touched the objects inside a wooden box, with the front covered by a white cloth that prevented visual contact with the stimuli. The box interior was divided in half, separating the hands and avoiding touch with both hands. Participants listened through headphones to cues that determined the beginning and end of the three seconds exploration time.

Procedure

Participants were instructed to freely explore each object with their non-dominant hand and to identify it as quickly as they could. The 30 participants were divided in two groups of 15 participants and each group touched either common or uncommon object set. Participants placed their hands, one in each side of the box division and were asked to place their dominant hand in a free, comfortable position, and their non-dominant hand in the bottom of the box with their palm upwards. Each object was placed directly on the participants non-dominant hand and they were allowed to start manipulating it at the moment that they heard the sound cue. After hearing the second sound they had to open their hand, enabling removal of the object. At this point in the task, if the participant had not yet provided a name for the touched object he or she had to say its name or, in case an identification had not occurred, had to verbalise that it was an unknown object.

RESULTS

An answer was considered correct when it reported the specific name of the object (e.g. *hammer* would be a correct answer and *tool* would be an incorrect answer) or any regional variation of its name. Figure 14 shows the values of correct identification and non responded trials (trials where participants did not provide an answer, declaring they did not knew the touched object). Correct identification is better for common than uncommon objects, *t* (28) = 11.00, *p* < .001, *r* = .901; and, the number of missed trials is higher for uncommon than for common objects, *t* (28) = −6.53, *p* < .001, *r* = .777.

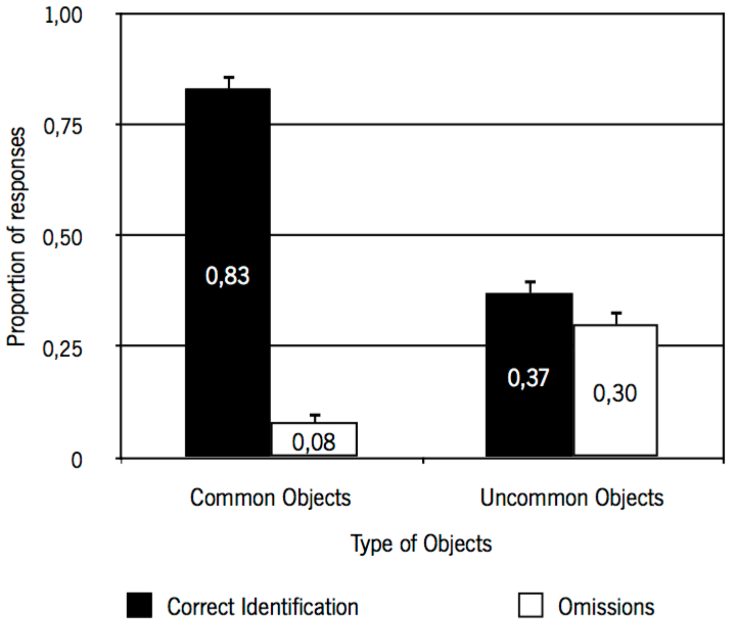

Figure 14: Correct identification and omissions according to object type

In Table 11 and Table 12 represent correct identification proportions for each object, according to object set. It is possible to observe that, for common objects, a proportion of .38 (41 objects) of the objects were correctly identified by all participants, while for uncommon objects this proportion lowers to .08 (7 objects).

Table 11: Identification data for each one of the items in the common objects' set

	Correct Identification		Correct Identification		Correct Identification
Adhesive tape	1,00	**Hole puncher**	0,78	**Screwdriver**	0,71
Bath puff	0,80	**Keychain**	1,00	**Shaving brush**	0,80
Bracelet	0,88	**Knife**	1,00	**Shoe brush**	1,00
Calculator	1,00	**Lamp**	1,00	**Shoehorn**	0,83
Candle	0,56	**Lantern**	0,92	**Small ball**	1,00
Cassette	0,78	**Lighter**	0,83	**Soap**	0,80
Cellular phone	0,45	**Lipstick**	1,00	**Soap-dish**	0,07
Cloth	1,00	**Lollipop**	1,00	**Spatula**	0,73
Clothespin	1,00	**Magnifier**	0,75	**Spoon**	1,00
Coffee cup	1,00	**Nail brush**	0,90	**Spun yarn**	0,80
Comb	1,00	**Nail clippers**	1,00	**Stapler**	1,00
Contact lenses box	0,43	**Nail polish**	1,00	**Staples remover**	0,71
Cork	0,56	**Notepad**	1,00	**Strainer**	0,90
Cork screw	0,88	**Nutcracker**	0,78	**Sunglasses**	0,92
Corrector pen	0,83	**Pacifier**	1,00	**Swimming cap**	0,73
Deodorant	0,86	**Painting brush**	1,00	**Tea bag**	0,25
Dish sponge	0,88	**Pc mouse**	1,00	**Three way plug**	0,85
Doll	1,00	**Pen**	1,00	**Tissue pack**	0,92
Drinking straw	0,90	**Pencil**	0,82	**Toothbrush**	1,00
Fork	1,00	**Pencil case**	0,83	**Toothpaste**	0,56
French clip	0,83	**Penknife**	0,56	**Tupperware**	0,00
Glass	0,92	**Phone charger**	1,00	**Tweezers**	1,00
Glasses case	0,90	**Plastic glove**	0,89	**Umbrella**	0,89
Glue stick	0,80	**Pliers**	0,27	**Wallet**	0,82
Hair claw	0,83	**Plush**	1,00	**Whistle**	1,00
Hairband	0,57	**Rasp**	0,86	**Wooden box**	0,92
Hairbrush	1,00	**Rubber**	1,00	**Wrench**	0,50
Hammer	0,80	**Saucer**	1,00	**Wristwatch**	1,00
Cream package	0,90	**Scissors**	1,00	**Yarn ball**	0,75
Headphones	0,50	**Scouring pad**	0,50	**Yogurt package**	0,78
Highlighter	0,70	**Screw**	1,00		

Table 12: Identification data for each one of the items in the uncommon objects' set

	Correct Identification		Correct Identification		Correct Identification
Badge	0,50	**Miniaturized ceramic hat**	0,10	**Plastic miniaturized spoon**	1,00
Calculator	0,00	**Miniaturized clay fruit bowl**	0,50	**Plastic miniaturized toilet**	0,43
Candle metal box	0,57	**Miniaturized duct tape dispenser**	0,11	**Plastic onion**	0,20
Carabiner	0,40	**Miniaturized frying pan**	1,00	**Plastic pen box**	0,22
Card deck	1,00	**Miniaturized helmet**	0,13	**Plastic pliers**	0,67
Cartridge	0,18	**Miniaturized jar**	0,17	**Plastic rasp**	0,40
Conch	0,50	**Miniaturized liquid soap package**	0,08	**Plastic robot toy**	0,08
Coral bath sponge	0,20	**Miniaturized milk pan**	0,44	**Plastic screw**	0,75
Decoration statue	0,22	**Miniaturized mop**	0,08	**Plastic Screw driver**	0,09
Flash drive	0,14	**Miniaturized perfume bottle**	0,00	**Plastic strawberry**	0,13
Floppy disk box	0,60	**Miniaturized photo camera**	0,00	**Plastic tomato**	0,50
Flower-shaped nail polish	0,00	**Miniaturized plastic bathtub**	0,30	**Plastic tube**	0,15
Garbage shovel	0,60	**Miniaturized plastic chair**	0,22	**Plastic walnut**	0,25
Garlic peeler	0,11	**Miniaturized plastic glass**	0,10	**Plastic wrench**	0,18
Hand fan	0,54	**Miniaturized plastic hairdresser**	0,11	**Pot**	0,67
Heart-shaped plastic box	0,57	**Miniaturized plastic handsaw**	0,50	**Rattan decoration ball**	1,00
Honey spoon	0,50	**Miniaturized plastic knife**	0,57	**Rounded remote control**	0,67
Horn	0,75	**Miniaturized plastic tractor**	0,33	**Small hourglass**	0,00
Large bracelet	1,00	**Miniaturized portable ashtray**	0,00	**Small snow globe**	0,17
Large pen	0,80	**Miniaturized tank**	0,30	**Soap dish**	0,50
Lip gloss package	0,00	**MP3 player**	0,29	**Stapler remover**	0,00
Massager	0,86	**Pan coaster**	0,67	**Toy mobile phone**	0,17
Medal	0,40	**Paperweight**	0,44	**Wall hanger**	0,33
Metric tape	0,40	**Photo holder**	0,20	**Wooden flute**	0,17
Miniaturized ashtray	0,44	**Plastic bracelet**	1,00	**Wooden hand mirror**	0,73
Miniaturized boat	0,18	**Plastic chili**	0,10	**Wooden plaques toy**	0,56
Miniaturized bucket	0,20	**Plastic miniaturized basket**	0,89	**Wooden spatula**	1,00
Miniaturized cake pan	0,30	**Plastic miniaturized maize ear**	0,11		

CONCLUSION

Participants, in average, were able to correctly identify .83 (SD = .03) of common objects and .37 (SD = .03) of uncommon objects. Clearly, there is an advantage in identification of common objects. In the three seconds exploration time that was allowed, most objects in the uncommon set were not correctly identified. The two sets are different and name encoding for the objects in the uncommon set seems to be very unlikely, since the participants show difficulty in naming the touched objects.