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HAPTIC LATERALITY AND MEMORY FOR VERBAL AND NON-VERBAL SHAPES

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DOCTORAL DISSERTATION

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ABSTRACT

Functional hemispheric asymmetry or laterality refers to the distinctive contribution of the two cerebral hemispheres during several cognitive processes. The left hemisphere is often found to display superiority in processing verbal material while the right hemisphere has an advantage in processing nonverbal material. In the somatosensory system, haptic laterality is reflected in differences in performance between hands in terms of accuracy and speed in various perceptual and cognitive tasks. Due to contralateral innervation, a left hemisphere advantage is manifested as superior performance in the right hand, and vice versa.

In the present thesis, haptic laterality was studied behaviourally by having participants perform haptic memory tasks using the right and left hand separately, with verbal (upper and lower-case letters) and nonverbal (nonsense) 2-dimensional shapes as stimuli. In Study 1, the effect of retention intervals on laterality was studied in haptic discrimination by investigating hand/hemisphere advantage for upper-case letters, geometrical shapes and nonsense shapes at 5, 15 and 30 s retention intervals. In Study 2, laterality in haptic discrimination was further addressed by introducing two levels of stimulus complexity within the verbal stimuli, that is, less complex upper-case letters and more complex lower-case letters. Study 3 examined haptic recognition memory and laterality for upper and lower-case letters and nonsense shapes.

The results showed that laterality effects were influenced by the verbal/nonverbal type of stimuli (Studies 2 and 3), and also by hand order of performance (Study 3) and retention time (Study 1). In Study 2, a clear left hand/right hemisphere advantage was found for nonsense shapes, while the right hand/left hemisphere advantage only approached significance for upper-case letters. In Study 3, more advanced memory performance of right hand/left hemisphere was found with upper-case letters, but only when the right hand performed the task after the left hand. The lower-case letters did not show any laterality effects. Across stimulus types, left hand/right hemisphere sustained haptic discrimination for up to 15 s, while the right hand/left hemisphere declined progressively in performance throughout all retention intervals (Study 1).

Altogether, the findings in this thesis showed that laterality effects in haptics existed but they were rather weak. This may be due to the predominantly spatial and sequential nature of the processing of the haptic sense. In addition, letters are haptically unfamiliar stimuli. Thus, verbal stimuli might be processed primarily as spatial objects, which can result in

diminished verbal coding and hence the lack of clear verbal laterality effect in haptics.

Overall, upper-case letters showed better performance than lower-case letters (Study 3) and nonsense shapes (Studies 1 and 3). Such superior memory of letters with less complex shapes (capital letters) may perhaps be due to their more effective dual (spatial and verbal) coding.

TIIVISTELMÄ

Aivopuoliskojen toiminnallinen epäsymmetria eli lateralisaatio tarkoittaa sitä, että aivopuoliskot osallistuvat eri lailla moniin kognitiivisiin toimintoihin. Vasen aivopuolisko on usein hallitseva verbaalisissa prosesseissa ja oikea ei-verbaalisissa. Tuntojärjestelmässä haptinen lateralisaatio näkyy käsien välisinä eroina kognitiivisten tehtävien suoritustarkkuudessa ja -nopeudessa. Vasemman aivopuoliskon hallitsevuus ilmenee oikean käden parempana suorituksena ja päinvastoin, koska hermotus risteää aivoista kehon vastakkaiselle puolelle.

Tässä väitöskirjassa tutkittiin haptista lateralisaatiota muistitehtävien avulla. Koehenkilöt suorittivat tehtävän erikseen oikealla tai vasemmalla kädellä. Osatyössä 1 tutkittiin eri muistiviiveiden (5, 15 and 30 s) vaikutusta kirjainten sekä geometristen ja merkityksettömien muotojen erotuskykyyn. Osatyössä 2 käytettiin isoja ja pieniä kirjaimia verbaalisten ärsykkeiden monimutkaisuuden tutkimiseen. Osatyössä 3 tutkittiin haptista tunnistusmuistia.

Tulokset osoittivat, että lateralisaatioon vaikutti ärsykkeiden verbaalisuus (2 ja 3), käsien suoritusjärjestys (3) ja muistiviive (1). Osatyössä 2 oikea aivopuolisko oli hallitseva merkityksettömien muotojen tuntoerottelussa ja vasen marginaalisesti isoille kirjaimille. Vasen aivopuolisko oli hallitseva isoille kirjaimille myös osatyössä 3, mutta vain kun oikea käsi suoritti muistitehtävän vasemman jälkeen. Pienille kirjaimille ei esiintynyt lateralisaatiota. Kaikille ärsykkeille oikea aivopuoliskon suoritus pysyi yllä 15 sekuntiin asti, kun taas vasemman laski muistiviiveen pidentyessä (1).

Kokonaisuudessaan väitöskirja osoittaa, että haptinen lateralisaatio on melko heikkoa. Syynä voi olla se, että tuntoaisti rekisteröi muodon vähitellen pala palalta aikasarjana, eivätkä kirjaimet ole kovin tuttuja tunnustelemalla. Voi siis olla, että verbaaliset ärsykkeet prosessoidaan ensisijaisesti spatiaalisesti eikä verbaalisesti, jolloin verbaalista haptista lateralisaatiota ei juurikaan esiinny.

Isot kirjaimet muistettiin ja eroteltiin paremmin kuin pienet kirjaimet (3) ja merkityksettömät muodot (1 ja 3). Niistä ehkä pystyttiin prosessoimaan sekä spatiaaliset että verbaaliset piirteet, ja tämä kaksoiskoodaus paransi suoritusta.

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CONTENTS

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following publications:

1. Stoycheva, P., & Tiippana, K. (2018). Exploring laterality and memory effects in haptic discrimination of verbal and nonverbal shapes. Laterality, 23 (6), 684-704. Doi: 10.1080/1357650X.2018.1450881

2. Stoycheva, P. L., Kauramäki, J., Newell, F.N., & Tiippana, K. (2020). Laterality effects in the haptic discrimination of verbal and nonverbal shapes. Laterality, 25 (6), 654-674. Doi: 10.1080/1357650X.2020.1800026

3. Stoycheva, P. L., Kauramäki, J., Newell, F. N., & Tiippana, K. (2021). Haptic recognition memory and lateralization for verbal and nonverbal shapes. Memory 29(8),1-15. Doi: 10.1080/09658211.2021.1957938

The publications are referred to in the text by their numerals.

1 INTRODUCTION

1.1 INTRODUCTION TO LATERALITY OF COGNITIVE FUNCTIONS

It is well known that the two brain hemispheres differ in how they process information. Even though both hemispheres are capable of processing similar information to a reasonable degree, each hemisphere has a processing advantage over the other for certain cognitive tasks or materials. This is known as functional hemispheric asymmetry or laterality.

The initial evidence for functional hemispheric laterality came from clinical studies (brain lesions), split-brain (commissurotomy) studies and studies with healthy individuals (Bradshaw & Nettleton, 1983 ; Mundorf & Ocklenburg, 2021 ; Ocklenburg & Gunturkun, 2017, for reviews). In order to examine the contribution of each hemisphere in various tasks, laterality research takes advantage of the functional anatomy of the sensory pathways through which the information from the senses is carried to the brain areas (Gazzaniga, 1995, 2005). In vision, the left visual fields of both eyes project to the right visual cortex and the right visual fields to the left visual cortex. In audition, the information received through each ear projects to both hemispheres, but the contralateral sensory paths are more direct and have more nerve fibres than the ipsilateral paths. In addition, the ipsilateral paths become inhibited when the acoustic information is perceived simultaneously from both ears (Hellige, 1993 ; Mildner, 2007). Tactual sense is predominantly contralateral : information perceived through the active discriminative touch (fingers) and stereognosis is fully lateralised (lemniscal system), while passive touch, pain and temperature are both contra- and ipsilateral (spinothalamic system). Thus, most of the information perceived through the visual fields, ears and hands is initially received in the contralateral hemisphere so that each half of the brain has predominant control over the opposite sensory side (organ). However, in healthy normal individuals the hemispheres do not operate independently, since the sensory information is transferred through the commissures that connect the hemispheres. Therefore, in cognitive tasks any difference in response times or accuracy between the visual fields, ears and hands can be interpreted as a delay or degradation of the sensory information during such transfer. Consequently, these differences are considered as a processing advantage of one of the hemispheres over the other for certain cognitive functions. For example, we could deduce that the left hemisphere has an advantage in word recognition tasks if the right visual field, ear or hand show better accuracy and/or faster reaction times than the left visual field, ear and hand.

The most prominent differentiation between the hemispheres refers to verbal versus non-verbal processing. In general, it is found that the left hemisphere has an advantage in processing verbal information, while right hemisphere advantage has been associated with non-verbal or spatial processing (see Mildner, 2007 ; Ocklenburg & Gunturkun, 2017, for reviews). This division of the functions between the hemispheres has been attributed to the well-known predominance of the left hemisphere for language functions in most right-handed people (Knecht et al., 2000 ; Somers et al., 2015). Thus, the left hemisphere advantage is expected and generally found when verbal information is perceived through the right sensory side (right visual field, ear, hand). These laterality effects have mostly been researched in vision and audition and much less in tactual/haptic modality.

In vision, there is a long list of evidence for the existence of a robust right-visual field advantage for visual recognition of verbal material for right-handed participants (Boles, 1981 ; Boles, Barth, & Merrill, 2008 ; Barca et al., 2011- for a review). For example, a typical visual half-field task is when the participants maintain their focus on a central fixation point on a screen and written words are presented briefly to the right and/or to the left of the fixation point. The words presented to the right visual field/left hemisphere are recognised more quickly and with better accuracy. This right visual field/left hemisphere advantage appears in various verbal tasks such as recognition after brief presentation, indication of certain letters from presented words, speed of reading the words aloud, distinguishing from nonwords, or meaning identification. The left-visual field/right hemisphere advantage is found in tasks with non-verbal material like lightness, hue and depth perception. Further, there is also evidence for left visual field advantage for even verbal material when that material (letters, words) is unfamiliar, perceptually degraded or visually confusing (Bradshaw & Nettleton, 1983 for a review). In these cases, it is suggested that the right hemisphere advantage appeared in order to facilitate the processing of the physical features of the stimuli.

In auditory modality, the dichotic listening procedure was employed to examine the contribution of each hemisphere by suppressing the ipsilateral paths. That is, the two ears simultaneously receive different acoustic stimuli. When those stimuli are of a verbal nature (words, syllables) the most common finding for right-handed participants is the right ear advantage and hence left hemisphere advantage. With non-verbal acoustic stimuli like environment sounds, melodies, tones and notes from musical instruments a left ear/ right hemisphere advantage is typically found (Bradshaw & Nettleton, 1983 ; Hellige, 1993 ; Mildner, 2007 for reviews).

1.2 HAPTIC PERCEPTION IS PART OF THE SOMATOSENSORY PERCEPTION

Haptics and touch in general are of great importance in daily life and yet their significance is underestimated. The complexity of the sense of touch allows us to perceive a wide range of properties of objects like shape, size, weight, texture, temperature and compliance. We constantly relay on touch in our everyday tasks: for example, when we decide whether a drink or a dish we are about to consume is at the right temperature, or which fruit is ripe, or when we look for our keys in a bag in a dark room. The access to the information received through our sense of touch is taken for granted and we usually start appreciating it more when we consider people who have experienced a loss of some of the other main senses, like vision and/or hearing.

The somatosensory system is represented by a group of sensory modalities: perception of pain, pressure, temperature, body position (proprioception), body movement (kinesthesia) and sense of touch (Kalat, 1992). Touch perception can be divided into tactile (passive) and haptic (active) perception (Kappers & Tiest, 2015). Tactile perception is the sense of touch which is perceived through the cutaneous receptors of the skin (mechanoreceptors and thermoreceptors) and refers to the simple contact which the skin makes with an object (Hertenstein & Weiss, 2011). Tactile perception is of great importance in the extraction of the material features of the objects, such as texture, hardness and temperature (Lederman & Klatzky, 2009). Haptic perception includes tactile perception plus the perception received through the kinaesthetic receptors in the muscles, joints and tendons. Thus, haptic perception is mostly understood as active touch or using the hand and the fingers for active exploration in order to recognise and identify the objects and the space around us (Lederman & Klatzky, 2009). Haptic perception is important in extracting the geometrical properties of the objects, such as shape and size. It is worth noting that haptics is not just a simple sum of tactile and kinesthetic perception but represents an integrative perception of the stimulus properties (material and geometrical) (Kaas, Stoeckel & Goebel, 2008). When an object is perceived through enclosure for example, multiple features of that object are extracted, such as shape, texture, weight and temperature (Plaisier, Polanen & Kappers, 2017).

Amongst the main factors that influence haptic perception is the nature of the stimuli presented (Fernandes & Albuquerque, 2012). Thus, with regard to stimulus type it is important to consider whether stimuli are familiar or unfamiliar, whether they present concrete objects or abstract shapes, whether they are verbal or nonverbal, and whether they are presented as 2D or 3D shapes. Haptic perception with familiar objects can be very precise. Thus, in the study of Klatzky, Lederman & Metzger (1985) the participants recognised with nearly perfect accuracy 100 everyday objects within 1-2 sec. According to Klatzky & Lederman (2003) familiar everyday objects are recognised as a whole in pattern recognition, while the perception of abstract stimuli seems to be less integrative and the various features of the abstract object are recognised as different features that need to be combined.

The haptic system has evolved for the three-dimensional world, and consequently two-dimensional objects can invoke constraints that can lead to poorer performance (Lederman, Klatzky, Chataway, & Summers, 1990). Thus, even the recognition of familiar everyday objects can become poor when those objects are presented in 2D shapes like raised line drawings or planar shapes (Lederman et al., 1990). For example, in the study by Lederman (1990) the recognition rate for 2D drawings of real objects was 34 %, in the study by Loomis, Klatzky, & Lederman (1991) it was 34 % and in a study by Klatzky, Loomis, Lederman, Wake, & Fujita (1993) it was 30 %. This low rate of performance was related to 2D versus 3D properties of the stimuli. There is evidence that recognition of real objects is facilitated by the ability to grasp the object with a greater number of fingers, which is possible with 3D shapes. That is because the 3D shapes provide cues of gradient of pressure as well as spatial location. Lawson & Bracken (2011) varied the availability of depth cues in object recognition task by choosing minimal (cookie cutter filled-in outlines), partial (squashed and half objects) and full (3D models) availability of depth information. Results showed that greater depth information produced faster and more accurate object recognition. In addition to the structural properties of their 3D shape (configuration and size), common natural objects also provide multiple cues related to their material properties, such as texture, hardness, temperature. When these objects are presented as 2D planar shapes or line drawings, there is no information about the third dimension, so that they give access mainly to the structural configuration in one plane. Furthermore, such 2D stimuli are usually controlled for material properties. According to Gibson (1966) the haptic system is especially well suited for examining material properties. When that information is reduced, haptic performance can be expected to be worse.

1.3 HAPTIC LATERALITY

Over the years, notable evidence has been collected for visual and auditory laterality. In contrast, there has been a significant gap in the empirical work on haptic lateralisation for a long time and currently there are only few studies addressing this topic.

Haptic laterality is based on the anatomical link between the neural projections of each hand to the contralateral hemisphere. Thus, by measuring and comparing the performance between each hand in cognitive tasks (e.g., shape discrimination), we can make conclusions about which hand and respective hemisphere has an advantage for that task or cognitive function. For example, there is evidence that the left hand is faster and more accurate than the right hand in nonsense shape discrimination tasks (Fagot, Lacreuse & Vauclair, 1997- for a review). That is evidence for a left hand-right hemisphere advantage in shape discrimination.

However, sometimes no laterality effects are found. For example, recognition of familiar objects did not show laterality (Craddock & Lawson, 2009; Yamashita, 2015). In Craddock & Lawson's (2009) study, right-handed participants haptically explored and named 48 familiar objects placed on a table in left and right orientation. The participants performed with the right hand only in half of the trials, and with the left hand in the other half. The exploration time was not limited but participants were told to aim to name the object as quickly and as accurately as possible. The results showed that performance (RTs and errors) between hands did not differ for any of the blocks or conditions (object directions) and thus no laterality effects were found. In a similar study by Yamashita (2015), right-handed participants used their left or right hand to haptically explore and name 100 common objects from 10 categories within a 60 s time limit. The results showed 90 % recognition rate and a lack of significant effect on errors of the hand used

However, laterality studies are mainly based on differentiation between verbal-nonverbal processing. Such laterality effects are less clear in somatosensation than vision and audition. In a review of research on tactual asymmetries, Fagot, Lacreus and Vauclair (1997) concluded that tactual laterality depends on the verbal-nonverbal nature of the task. Most studies using nonverbal material have discovered evidence for left hand/right hemisphere advantage in tasks involving nonverbal spatial processing. With verbal material, some contradictory results have been found. For instance, instead of the well-known left hemisphere advantage a left hand/right hemisphere advantage for verbal stimuli has been found (O'Boyle & Murray, 1988; O'Boyle, Van Wyhe-Lawler & Miller,1987; Walch & Blanc-Garin, 1987) as well as a lack of any advantage (Witelson, 1974, Summers & Lederman, 1990 for a review). For example, O'Boyle et al. (1987) found a left hand/right hemisphere advantage when upper-case letters were traced on the palms of the hands of the participants. Also, there is inconsistency of the results from studies using Braille letters as there is evidence for both left hand/right hemisphere advantage (e.g., Rudel, Dencku, & Hirsch, 1977) and right hand/ left hemisphere advantage (e.g., Millar, 1984) or lack of any advantage (Summers & Lederman, 1990, - for a review). One of the first explanations for the lack of consistent left hemisphere advantage for haptically perceived verbal material was proposed by Witelson (1974). She suggested that in haptics, letters are processed initially as spatial stimuli and only subsequently is that information transformed into a verbal code. Thus, if the right hemisphere is also initially involved in the processing of verbal stimuli, the left hand/ right hemisphere advantage for haptically perceived letter stimuli can be expected.

Borgo, Semenza, & Puntin (2004) have proposed that the left hemisphere advantage for verbal material in haptics depends not simply on the verbal/nonverbal nature of stimuli but on the verbal/nonverbal encoding strategy as well. That is, even for verbal stimuli like letters, a right hemisphere advantage can be expected if the task is to encode the letters in a spatial way, as for example, to compare their geometrical shape rather than their verbal meaning. Thus, Borgo, Semenza, & Puntin (2004) aimed to control for the encoding strategy in a haptic study where upper and lower-case letters were used as verbal material. There were two task conditions with the letter stimuli: a verbal one where two letters had to be compared based on their verbal names regardless of their graphemes (i.e., “A-a” as same), and a spatial condition where the letters had to be differentiated based on their physical configuration or graphemes (i.e., “A-a” as different). In this way, the authors aimed to compare verbal versus spatial encoding strategies applied to the same verbal stimuli. Indeed, when a verbal strategy was explicitly introduced through the “name identity” task for letters, a right hand/left hemisphere advantage emerged, in agreement with the well-known verbal laterality effect. In contrast, there was no difference between hands when the same letter pairs were compared based on their grapheme identity. Similarly, Passarotti, Banich, Sood, & Wang (2002) also varied the coding strategy during exploration of geometrical shapes. That study also found evidence that laterality effects in haptic might depend on the coding strategy imposed by the task. Thus, when the geometrical shapes had to be compared categorically (i.e., whether two shapes belong to the same category of a triangle) a left hemisphere advantage appeared. In contrast, the right hemisphere advantage emerged when comparison of the shapes was based on their physical configuration (whether two triangles are identical). These two studies suggest that in addition to the verbal/nonverbal nature of the stimuli, another factor which might influence the direction of laterality is the coding strategy imposed by the task.

1.4 HAPTIC MEMORY

1.4.1 MEMORY PROCESSES AND THEORIES

Memory is a term used to describe the complex ability to encode, store and retrieve information (Squire, 2009). The information can enter the memory system through different senses (e.g., vision, audition, touch) and thus we can differentiate visual, auditory and tactile memory. One of the most established models of human memory is the multi-store model of Atkinson and Shiffrin (1971; Malmberg, Raaijmakers, & Shiffrin, 2019, - for a review), which describes the memory process in terms of sensory, short-term and long-term memory. These differ in two main ways: duration and capacity. Therefore, memory is usually examined in terms of decay of information over time and in terms of how much information can be stored. Below I will focus on research using tasks where external stimuli are presented, and the task is to try to remember as many of them for subsequent recognition.

Sensory memory is the first phase, when information perceived from an external stimulus is retained in great detail without any manipulation and for very brief moments, around milliseconds in vision (Sperling, 1960; Tripathy & Ögmen, 2018) and around 2 seconds in audition (Sabri, Kareken, Dzemidzic, Lowe, & Melara, 2003). For the tactile sense, the sensory stage has been suggested to be between 5 to 10 s (Kaas, Stoeckel & Goebel, 2008- for a review).

Some information from the sensory store enters short-term memory. The short-term memory acts as a temporary storage, and it retains a limited amount of information in a very accessible form for a short time, usually some seconds. The information is thus available for rapid retrieval but is soon forgotten if it is not rehearsed actively. The more that information is rehearsed in the short-term storage, the more likely is to be transferred to long-term memory (Sherwood, 2015). The most prominent model of short-term memory is Baddeley's model of working memory (Baddeley and Hitch, 1974, 1986). Working memory is a type of memory which is used to hold and manipulate activated information (either new or previously stored) for immediate use. According to Baddeley's model, it consists of a phonological loop that generally maintains verbal information, a visuospatial sketchpad that processes visual and spatial information, and the central executive, which connects and coordinates both.

Some of the information from the short-term memory enters the long-term memory where it is retained over an extended period of time like days or years (Sherwood, 2015), and the amount of information retained is practically indefinite (Zlotnik & Vansintjan, 2019). The information in long term memory is stored in an organised way, through a process of rehearsal and associations.

For example, there are different representations for visual, auditory or haptic memories. This organisation facilitates the process of retrieving modality-specific information. It usually takes a longer time to remember something from long-term memory than from short term memory as the capacity of long-term memory is vast.

Memory depends strongly on the type of information that is retained. The familiarity and complexity of stimuli are among the factors that influence memory performance. The verbal/nonverbal nature of the memorized materials is also a very important factor. Memorising verbal versus nonverbal/pictorial materials is the main focus in the dual coding theory (DCT) developed by Paivio (2007 for a review). According to the DCT, there are two main memory processing systems, one responsible for verbal and another for nonverbal information. The nonverbal system operates in a direct, analogous way and depicts the information as spatial representations. The verbal one is specialised for language and sequential processing. Both systems are independent but work in cooperation, and they have additive functions. That is, when certain material is coded dually, verbally and spatially, it is remembered better. If we relate the two memory processing systems from DCT with the multi-store model of memory, we could presume that the verbal vs nonverbal coding of stimuli most likely refers to processing at later stages than the sensory stage. That is, the DCT relates to the short-term and long-term memory. Similarities could also be seen between Baddeley's model of working memory and the DCT in that both models have separate components for spatial and verbal processing. Like the multi-store model, in DCT information enters the verbal and nonverbal memory systems through different sensory modalities. However, most of the studies in support of this theory have been conducted in vision.

One important part of verbal processing in vision is the perception of letters. It has been proposed that visual letters are processed at four interacting levels in the brain (Madec et al., 2016). The first level processes elementary features of the stimuli. At the second, perceptual level, a template representation of letters is formed. The next level is the abstract or shape-invariant level, where processing is independent of the specific features of the letters like font and case. The highest level is the phonological one at which the letter is coded by its name. Linking these processing levels to DCT, we could assume that the verbal processing in DCT may happens mainly at the last phonological level.

Most studies on the memory process have been conducted in vision and audition while the tactile/haptic sense has received less attention. Despite the importance of somatosensation in everyday life, very little is known about the operation of tactile or haptic memory. This thesis investigates both the duration and capacity of haptic memory. Regarding duration, it focuses on the early haptic memory traces, and regarding capacity, it explores haptic recognition memory.

1.4.2 DURATION OF HAPTIC TRACES

It is still unclear how long the different memory stages in haptics last. The duration of the memory trace is usually studied through a delayed discrimination task in which two stimuli are presented successively with a retention interval between them. Typically, a response is required as to whether the stimuli are the same or different, and the retention interval is varied. In the tactile modality, most studies have used nonverbal stimuli to investigate the effects of retention intervals in various discrimination tasks. For instance, Millar (1974) used three-dimensional nonsense shapes in a pair discrimination task with retention intervals of up to 30 s. In half of the trials, the retention times were filled with interference tasks: finger-tracing shapes, counting backwards and arranging barrels. In the other half mental rehearsal was used during the retentions. The results showed that only after 5 s retentions, the rehearsed but not interfered condition showed improved discrimination for up to 30 s retentions. In agreement with these results, a similar study by Sinclair & Burton (1996) compared vibrotactile stimulus discrimination with unfilled and filled with distractor task (counting backward by threes) trials for up to 30 s retentions. Results showed a rapid decay of accuracy performance from 0.5 to 5 s retention but after 5 s the decay was slower for unfilled trials. Because the first sensory memory stage is believed to not be affected by rehearsals, the results from these two studies suggest that the sensory haptic/tactile memory store may last around 5s. However, other tactile studies found different retention gradients. For instance, abstract, L-like shapes are better discriminated at a retention time of 0 s compared to 15 and 30 s (Woods, O'Modhrain & Newell, 2004). Haptic orientation matching performance for bar-shaped objects is maintained up to 10 s (Kaas, van Mier & Goebel, 2007). Haptic discrimination performance of abstract "mice" plastic shapes is equivalent between 3 and 15 s (Craddock & Lawson, 2010). Discrimination of simple geometrical shapes is sustained up to 20 s (Bowers, Mollenhauer & Luxford, 1990). Complex LEGO blocks are discriminated with constant performance for up to 15 s (Kiphart, Hughes, Simmons & Cross, 1992). Also, passive tactile discrimination of grating orientations across various inter-stimulus intervals maintains accuracy for up to 15 s retention (Yu, Yang & Wu, 2013). Altogether, these studies show that the duration of the haptic/tactile memory traces for non-verbal items most probably vary for the wide range of tactile stimuli but may last from around 5 s up to 15-20 s.

1.4.3 HAPTIC RECOGNITION MEMORY

Haptic recognition memory tasks are widely used to study memory capacity. In the initial study phase of a classic haptic recognition memory task, the participants are presented with a set of stimuli to be felt and memorised haptically. In the following retrieval (recall or test) phase the same stimuli are presented again but this time intermixed with an equal number of new ones in a random order, and the task is to recall the previously encountered stimuli by labeling each stimulus as “old” or “new”. A simple way to express the results is in terms of the number of items remembered, which is old stimuli recognised as old. However, by presenting the results simply in this way an important factor is neglected: the response bias. That is, some participants might prefer one response over the other, for example the response of “old”. Results should be expressed in terms of d’ of SDT, which is a bias-free estimate of performance (Macmillan & Creelman, 2005). If there is no bias in performance, then it is acceptable to present the results as the number of items remembered, which is understood as capacity. Recognition memory tasks are often used to measure memory capacity but checking for bias in performance is often overlooked.

Haptic memory capacity depends strongly on the type of stimuli used. One factor influencing performance is the familiarity of the objects. Thus, haptic memory for familiar everyday items has proven to be very precise (Hutmacher & Kuhbandner, 2018; Klatzky, Lederman, & Metzger, 1985; Heller, Adams, Shuemaker, & Graven, 2020). In the study by Hutmacher & Kuhbandner (2018), memory performance for 168 common everyday objects felt for 10 s each reached 94 %. Moreover, memory performance was still high at 85% correct when tested unexpectedly one week after the first test. In contrast to this nearly perfect performance for familiar objects, recognition memory for unfamiliar nonsense stimuli is poorer. For example, in the Newell, Ernst, Tjan & Bülthoff (2001) haptic study the participants were presented with a set of four 3D abstract shapes (constructed from LEGO bricks) to be felt for 60 s each in the encoding phase. The capacity was 3 remembered items from a test set of 8 (four new intermixed with old). As the number of objects to be remembered was quite low (four) this result showed that haptic recognition memory for complex unfamiliar objects can be quite poor. The study by Ballesteros, Bardisa, Millar & Reales (2005) found direct evidence that familiar objects are better recognised than nonsense objects, at least in children between 6 and 13 years of age. In one of the experimental tasks, 6 real objects were used as familiar stimuli in the encoding and retrieval phase, while in a comparable task 4 nonsense 3D plastic shapes were used as unfamiliar stimuli. In both experiments a 5 min distractor task (forming piles from matches) was introduced between encoding and retrieval. Results revealed that for children older than 6 years, performance with familiar shapes reached ceiling effect, while the performance with nonsense shapes improved with age but without reaching ceiling effect.

1.5 MEMORY AND LATERALISATION

It has been hypothesised that laterality effects become more robust in later memory phases, after the initial sensory stage (Moscovitch, 1978). Evidence for this hypothesis has come mainly from visual studies where stronger laterality effects were found at longer retention times (Bradshaw & Nettleton, 1983 for a review; Evans and Federmeier, 2007; Oliveira, Perea, Ladera, & Gamito, 2013). Moscovitch (1979) has suggested that the first sensory stage of the memory process is related more to the processing of the low-level sensory characteristics of the stimuli and both hemispheres often show equal performance at this stage. The later memory stages are associated with more semantic encoding (wherever possible) and creating memory traces that can become more stable through rehearsal and cognitive transformations. At this later stage, the two hemispheres mostly tend to show processing differences (Moscovitch, 1979 for a review). Similarly, in their review of somatosensory asymmetry, Fagot, Lacreus and Vauclair (1997) concluded that asymmetries are usually not found at early sensory stages but they most likely could appear at the later stages, which are associated with post-sensory factors like cognitive and memory loads. Moreover, the laterality effects in these tasks are left hand-right hemisphere advantages in most cases.

Evidence for laterality effects in memory tasks has been found in cortical studies of the visual domain (Esteves et al., 2020- for a review). Thus, left-lateralised frontal cortical activation is found for encoding and retrieval of verbal material and right-lateralised frontal activation for non-verbal material (Kelley et al., 1998; Wagner et al., 1998). For example, in the Wagner et al. (1998) study, participants performed a memory recognition task for visually written words and for visually-presented texture stimuli that were difficult to verbalise. The results revealed greater left inferior prefrontal activation for encoding and retrieval of words, whilst non-verbal visual stimuli invoked greater right inferior prefrontal activation. We might speculate that similar process in haptics might also involve the hemispheres differentially, depending on the verbal/non-verbal nature of the task.

Some fMRI studies which did not explicitly address laterality have found some lateralised activations in haptic memory tasks (Stoeckel, 2003, 2004; Peltier et al., 2007; Ricciardi et al., 2006). In those studies, sometimes only the right hand was used to explore stimuli (Stoeckel, 2003, 2004) and sometimes both hands were used, but without differentiating between their performance (Ricciardi et al. 2006). For instance, Ricciardi et al. (2006) used a spatial discrimination task in which participants explored either 2D (squares) or 3D (cubes) objects for 10 s with both hands at the same time and gave a same/different response. Greater left than right activation was found in the middle prefrontal cortex (BA9, 6 and 44). It remains unclear whether there is a left hemisphere advantage in haptic memory for these shapes.

With regard to memory phases, a behavioural study addressing laterality in haptics showed that the order of the responding hand can influence the occurrence of lateral effects (Oscar-Berman, Rehbein, Porfert, & Goodglass,1978). In that study, upper-case letters, digits and line orientations were explored dichaptically (one stimulus in each hand simultaneously). Responses were given for each hand in each trial. In half of the trials participants had to answer first with the left hand and in the other half with the right hand. The expected right hand-left hemisphere advantage for letters and left hand-right hemisphere advantage for lines as nonverbal stimuli emerged only for the hand which was second in order in giving response. These results were explained in relation with the memory phases. The responses collected from the first hand were interpreted as measures of initial sensory processing. That is, the first hand response reflected the first sensory phase from the memory process while responses of the second hand were thought to reflect later memory processes. Hence, hand order might be an important variable influencing laterality effects.

2 AIMS AND HYPOTHESES OF THE PRESENT STUDY

The overall aim of this thesis was to investigate haptic laterality for verbal (letters) versus nonverbal (nonsense) stimuli in memory tasks. Performance was examined separately for each hand, which allowed us to compare which hand-hemisphere showed better performance. Results were always analysed in terms of d'.

The laterality hypothesis was that performance with letter stimuli will invoke right hand-left hemisphere advantage while performance with nonsense shapes will show left hand-right hemisphere advantage. In addition, it was expected that performance with letters would be better than that with nonsense shapes because of dual coding. That is, it was assumed that letters are coded verbally and spatially, which produces better performance compared to nonsense stimuli, for which only spatial coding was expected. There might also be other laterality effects, that is, any advantage in performance with one hand compared to the other hand.

The aim of Study 1 was to examine the hand/hemisphere advantage and the duration of haptic traces in the discrimination of verbal stimuli (upper-case letters), geometrical shapes (Euclidian shapes) and nonverbal (nonsense) shapes. That task required maintaining a stimulus in memory for 5, 15 and 30 s and comparing it with the next one, after which a response was given for whether the stimuli were same or different. It was expected that hand/hemisphere laterality effects would become more robust at longer retention intervals. It was expected that letters would be better discriminated than nonsense shapes due to possible dual coding (verbal and spatial).

The aim of Study 2 was to investigate the hand-hemisphere advantage for discrimination of upper and lower-case letters versus nonsense shapes, and thus to examine how complexity of the verbal stimuli in terms of physical shape would influence the haptic performance and hand-hemisphere advantage. In order to do this, the upper-case letters were designed as less complex than the lower-case letters in terms of orthographic shape. It was expected that upper-case letters would result in better performance than lower-case letters, which were more complex. Also, a laterality effect was expected in terms of better performance with the right hand than the left for both letter stimuli, and better performance with the left hand than the right for nonsense shapes. Also, it was expected that both letter types would be better remembered than nonsense shapes due to possible dual (verbally and spatially) coding.

The aim of the third study was to investigate haptic recognition memory for upper and lower-case letters versus nonsense shapes. We expected laterality effects for all stimulus types and better recognition memory for both letter stimuli compared to nonsense shapes due to dual encoding. We also expected better recognition memory for upper-case letters than lower-case letters due to upper-case letters being less complex than lower-case letters.

3 METHODS AND RESULTS OF STUDIES 1-3

3.1 STUDY 1: LATERALITY AND MEMORY EFFECTS IN HAPTIC DISCRIMINATION OF VERBAL AND NONVERBAL SHAPES

3.1.1 AIM

In Study 1 we examined whether the right hand has an advantage in verbal stimuli (upper-case letters) and left hand in nonverbal (nonsense) stimuli in a haptic discrimination task with different retention intervals. In addition, geometrical (Euclidian) shapes were used as a third type of stimuli which were presumed to consist of approximately equal verbal and nonverbal elements. There were three retention intervals between the stimuli to be discriminated: 5, 15 and 30 s. The aim was to investigate the duration of haptic memory traces for verbal and nonverbal shapes. The aim was also to examine whether and how the laterality effects for verbal and nonverbal shapes interact differentially with the three retention intervals.

3.1.2 METHODS

Twenty-four right-handed individuals (11 women, mean age 25 years) participated in the experiment. All participants were native speakers of Bulgarian. None of them reported dyslexia or any neurological disorder.

Stimuli consisted of wooden shapes (~4 cm x 4 cm x 0.7 cm), glued centrally to wooden boards (10 cm x 10 cm x 0.3 cm). Participants (blindfolded during the experiment) sat at a table with palm and fingers resting on a hand pad (placed centrally in front of them). Following an auditory signal, participants lifted their palm slightly prior to the placement of the stimulus. Auditory signals indicated when to start and stop exploring each stimulus.

There were 18 experimental blocks (60 trials each) resulting from three stimulus types (letters, geometrical, nonsense), three retention intervals (5, 15, and 30 s) and two exploration hands (left and right). Participants were blindfolded during the experiment and performed a same/different discrimination task for pairs of stimuli (30 same + 30 different pairs per block). That is, in each block, they explored one stimulus at a time with their left or right hand, followed by a retention interval after which a second stimulus was explored. Each stimulus was explored for 1 s through active touch with all fingers. Immediately after the second stimulus was explored, a response was required: pointing one finger for a response of “same” and two fingers for “different”.

3.1.3 RESULTS AND DISCUSSION

Results for d’ in haptic discrimination of three stimulus types (a) at three retentions (b) with left and right hand (c) are shown in Figure 1. Analyses for values of d’ (discriminability index) were conducted with repeated measures ANOVA by stimulus type (letters, geometrical shapes, nonsense shapes), retention intervals (5, 15, and 30 s) and hand (left and right) as factors.

There was a significant main effect for stimulus type [F (2, 44) = 15.7, p< .001, Fig. 1a]. Pairwise comparisons showed that geometric shapes (t= .463, p< .001) and letters (t= .376, p< .001) were better discriminated than nonsense shapes and there was no difference in performance between letters and geometric shapes.

A main effect of retention interval was also found [F (2, 44) = 8.75, p= .002, Fig. 1b]. Retention time of 30 s led to worse performance compared to 5 s (t= .491, p= .009) and 15 s (t= .341, p= .02) retentions, with no difference between 5 s and 15 s retention times.

No main effect was found for hand [F (1, 22) = .200, p= .659], but there was interaction between hand and retention time [F (2, 44) = 3.909, p= .03, Fig. 1c]. Pairwise comparisons revealed that right-hand performance was significantly better at 5 s compared to 15 s retention time (t=.303, p= .033) and 30-s retention time (t= .566, p= .003) while the left hand maintained the performance level between 5 and 15 s and decreased performance only at 30 s compared to 15 s retention time (t= .420, p< .01).

The results showed that the verbal/nonverbal nature of stimuli is an important factor in haptic discrimination. Our results suggest that haptic performance may improve if haptic stimuli can be dually coded, spatially and verbally. This is easier for verbal shapes like letters and geometric shapes that can be easily named. If the verbalisation factor is reduced as is the case with nonverbal nonsense shapes, haptic performance may worsen significantly. Further, evidence was found in support of the hypothesis that laterality effects are influenced by retention intervals. Thus, the left hand-right hemisphere sustained its performance for up to 15 s retention time regardless of stimulus type. In contrast, right hand-left hemisphere suffered a progressive performance decrease with increasing retention times. Therefore, it might be that left hand-right hemisphere is capable of retaining the haptic shape of the stimuli for a longer time than right hand-left hemisphere.

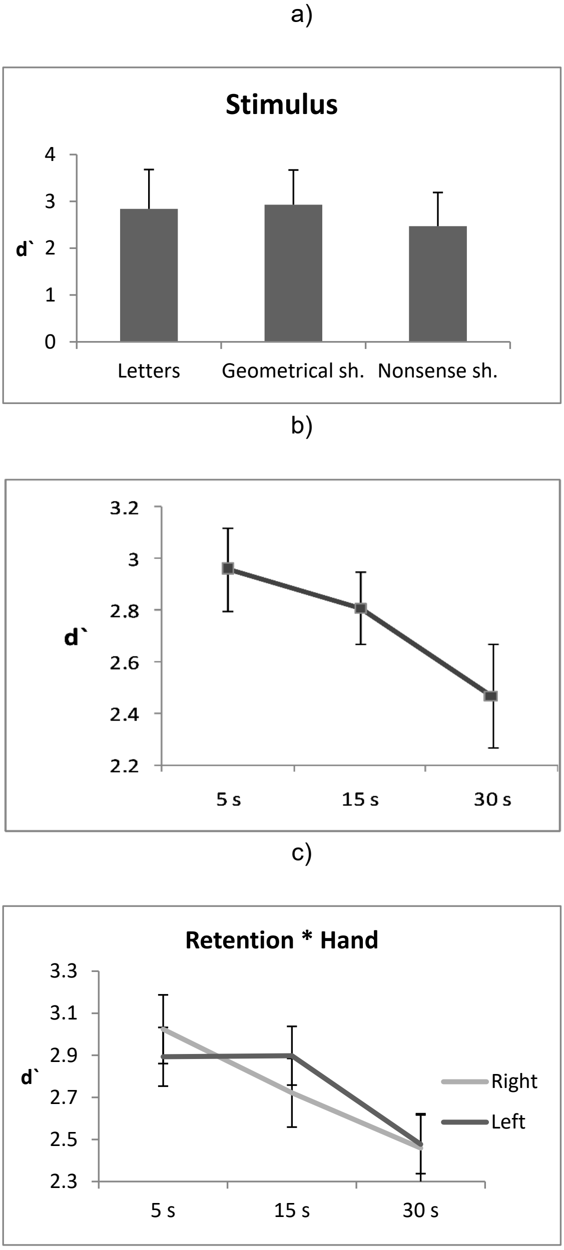


Figure 1 Performance (d') in unilateral haptic memory discrimination task for letters, geometrical shapes and nonsense shapes: a) Haptic discrimination for letters, geometrical shapes and nonsense shapes across retention and hands; b) Unilateral haptic discrimination at 5, 15 and 30 s retention times across stimulus types and hands; c) Unilateral haptic discrimination for each hand as a function of retention time. Error bars denote the standard error of the mean at $p < .05$. (reproduced with permission from the publisher, Stoycheva & Tiippana, 2018)

3.2 STUDY 2: LATERALITY EFFECTS IN THE HAPTIC DISCRIMINATION OF VERBAL AND NONVERBAL SHAPES

3.2.1 AIM

In study 2 we further investigated haptic laterality for verbal (letters) and nonverbal (nonsense) shapes in haptic discrimination. Moreover, we introduced stimulus complexity into the verbal stimuli as we included two letter types: upper- and lower-case, the latter being verbally identical with upper-case but designed with more complex shapes. We expected to find a left hand-right hemisphere advantage for nonsense shapes and a right hand-left hemisphere advantage for letters. Also, by introducing complexity we sought to examine whether the verbal factor determines the performance for letters or whether complexity differentiates the performance between two letter types regardless of verbality. That is, if complexity plays an important role, then there would be a significant difference in haptic performance between upper- and lower-case letters. However, we expected that performance with both letter types would be better than nonsense shapes due to dual coding (verbal + spatial).

3.2.2 METHODS

The participants were 24 right-handed students from the University of Helsinki. Their mean age was 26.3 (SD= 7.03) years (20 females). All participants spoke the Finnish language as their mother tongue. None reported neurological, learning, memory or sensory deficits.

All stimuli were raised shapes which were 3D printed from gray plastic and were 4 cm in length, 4 cm in width and 0.7 cm in depth. Each stimulus was glued onto an individual Plexiglass platform measuring 10 cm x 10 cm x 0.3 cm. Participants wore black glasses that prevented them from seeing the stimuli before and during the experiment. The experimental procedure was the same as in Study 1 with the addition that in this study the responses were recorded with a Cedrus RB-840 response box, positioned centrally behind the hand pad, and presentation software (Neurobehavioral systems, Albany, CA, USA) was used to provide auditory signals for the timing of the stimulus exploration.

The experimental task was same as in Study 1, that is, continuous discrimination of pairs of stimuli. However, in study 2 the retention interval between stimuli was fixed at 15 s. Participants explored with one hand only one stimulus at a time for 1 s, and after 15 s a second stimulus was explored for

1 s, which had to be compared with the first one. Response for stimuli being same or different was given.

Each participant performed 6 blocks of trials resulting from 3 stimulus types (upper-case letters, lower-case letters and nonsense shapes) and both hands (left and right hand). Each block consisted of 60 pairs of stimuli (30 same and 30 different).

Response times were also recorded, and they are reported in the article for Study 2. For the purpose of clarity and keeping the focus on the main measurements in each study, they are not reported in this thesis.

3.2.3 RESULTS AND DISCUSSION

Results for d' in haptic discrimination of upper-case letters, lower-case letters and nonsense shapes with left and right hand are shown in Figure 2. Repeated measures ANOVA was conducted on values of d' as dependent variable and stimulus type (upper-case letters, lower-case letters, nonsense shapes) and hand (left and right) as independent factors. There was no main effect of stimulus type or hand for d'. However, there was significant interaction between these two factors [$F(2,46) = 7.39$, $p < .001$, Fig. 2]. The pairwise comparisons revealed that performance with nonsense shapes was significantly better with the left hand than the right ($p < .01$). Also, performance with upper-case letters showed marginally better performance with the right hand than the left even though this tendency did not reach significance ($p = .054$). Further, performance with upper-case letters was better than performance with lower-case letters ($p < .01$).

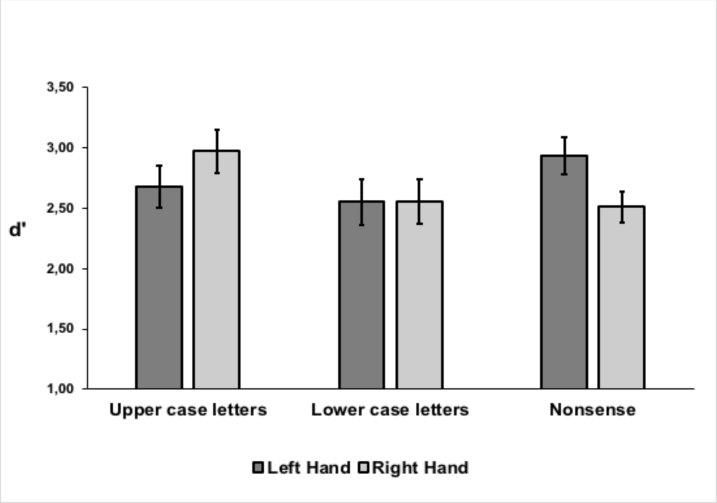


Figure 2 Performance (d’) in the haptic discrimination task for three types of stimuli: upper case letters, lower case letters and nonsense shapes for each of the hands. Error bars denote the standard error of the mean at $p<0.05$. (reproduced with permission from the publisher, Stoycheva et al., 2020)

This study found clear evidence in support of the hypothesis for left hand-right hemisphere advantage in the haptic processing of nonverbal material. In contrast, we did not find clear support for the right hand/left hemisphere advantage for verbal material. Even though for upper-case letters there was a trend for better right- than left-hand performance, this did not reach significance. This suggests that the lateralisation of verbal material in haptics is weak. Further, lower-case letters were discriminated worse than upper-case letters and their performance was as poor as that with nonsense shapes. The difference between upper and lower-case suggests that complexity of the letter shape also influences lateralisation in haptics. Thus, more complex letter shapes are more likely to be processed spatially rather than verbally. In such a case, the right hemisphere may initially be involved in their processing, which can reduce the verbal processing by the left hemisphere, and therefore no lateralisation effect or tendency appears. Hence the equal performance of the lower-case letters with the nonsense shapes.

3.3 STUDY 3: HAPTIC RECOGNITION MEMORY AND LATERALISATION FOR VERBAL AND NONVERBAL SHAPES

3.3.1 AIM

This study investigated haptic recognition memory and laterality for verbal and nonverbal shapes. The aim was to examine whether haptic recognition memory depends on the verbal-nonverbal nature of stimuli. The aim was also to explore the interaction between haptic laterality and haptic recognition memory. Letter stimuli were expected to reach better performance than nonsense shapes due to possible dual coding (verbal and spatial). A right-hand advantage in recognition memory was also expected for letters with a left-hand advantage for nonsense shapes. We also aimed to examine whether there would be a difference in performance between the hands depending on which hand first performed the task.

3.3.2 METHODS

Thirty right-handed adults (18 female) aged between 18-50 years old (M= 34; SD=8.7) participated in the study. All spoke Finnish as their mother tongue. None reported neurological, learning, memory or sensory deficits.

All stimuli were 3D printed from gray plastic with the approximate dimensions of 4 cm in height and 4 cm in width and 0.7 cm in depth. Each stimulus was glued onto a metal-coated platform of 10 cm x 10 cm x 0.3 cm. The setup of the apparatus was the same as in Study 2.

The experimental task was an old/new recognition memory task. In the first encoding phase, a sequence of 13 stimuli was presented one at a time for haptic exploration with one hand for 1 s. In the following recognition memory phase, participants explored another sequence of stimuli (26, half new) with same hand for 1 s. A response was given after each stimulus for whether the stimulus explored was old (explored in the encoding phase) or new.

Similar to Study 2 we used three stimulus types: upper-case letters, lower-case letters and nonsense shapes. Each participant performed 6 blocks of trials resulting from three stimulus types (upper-case letters, lower-case letters, and nonsense shapes) and exploration hand (left and right). Half of the participants performed the first three blocks (one block per stimulus type) with their left hand first and subsequently the same blocks with the right hand, while the other half performed their tasks in the opposite order.

Response times were recorded, and they are reported in the article for Study 3. For the purposes of clarity and keeping the focus on the main measurements in each study, they are not reported in this thesis.

3.3.3 RESULTS AND DISCUSSION

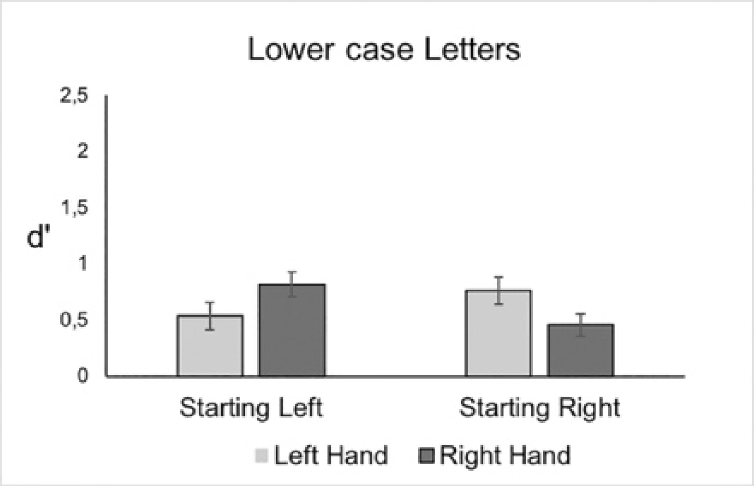
Results for d' for the left and right hand under two conditions, starting with left and starting with right hand for a) upper-case letters b) lower-case letters and c) nonsense shapes, can be seen in Figure 3. A mixed model ANOVA was conducted with stimulus type (upper-case letters, lower-case letters, and nonsense) and hand (left and right) as within-subjects factors and starting hand (which hand performs the task first) as a between-subjects factor. The main effects of stimulus type [F(2,56) = 46.6, p<.001, η2 = .63] and starting hand F(1,28) = 5.2, p=.03, η2 = .16] were significant but no significance was found for exploration hand [F(1,28) = 1.3, p= .26, η2 = .04]. However, there was an interaction between exploration hand and starting hand [F (1,28) = 16.01, p<.001, η2 = .36] as well as a three-way interaction between stimulus type, exploration hand and starting hand [F (2,56) = 4.5, p<.02, η2 = .14]. The pairwise comparisons for stimulus type revealed that performance with upper-case letters [mean d'=1.6] was better than that with lower-case letters [mean d'= .65; p< .001) and nonsense shapes [mean d'= .60; p< .001]. Moreover, there was no difference in performance between lower-case letters and nonsense shapes (p=1). Further pairwise comparisons in the three-way interaction revealed that, only for upper-case letters, the right hand was better than the left when the left hand was first to explore the stimuli (p< .01, Fig. 3).

Because there was no bias in the performance, the results from this task can also be expressed in terms of capacity, that is, the number of items which were correctly remembered from sequence of 13 shapes. Thus, on average the participants recognised 9.7 (left hand) and 9.8 (right hand) upper-case letters, 8.2 (left hand) and 7.8 (right hand) lower-case letters, and 7.6 (left hand) and 7.9 (right hand) nonsense shapes. One sample t-test showed that hit rates exceeded chance level (6.5 items) under all conditions (all p< .01).

a)


Upper case Letters
*
2,5
2
1,5
1
0,5
0
d'
Starting Left
Starting Right
Left Hand
Right Hand

b)


Lower case Letters
2,5
2
1,5
1
0,5
0
d'
Starting Left
Starting Right
Left Hand
Right Hand

c)

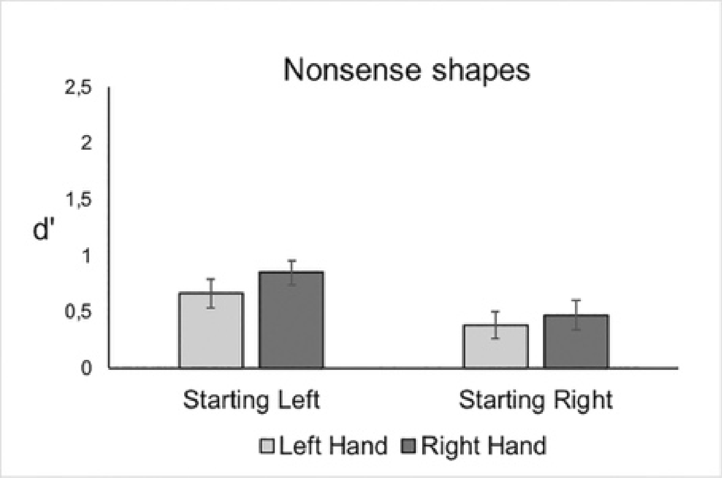


Figure 3 Haptic recognition memory performance d’ for the left and right hand in two conditions, starting with left and starting with right hand for a) upper case letters, b) lower case letters, and c) nonsense shapes. Error bars represent +/-1 SEM. (reproduced with permission from the publisher, Stoycheva et al., 2021)

These results suggest that complexity of the letter shapes influences haptic recognition memory. Thus, if letters are presented as more complex shapes (lower-case letters), they might be encoded mainly spatially and less verbally. Thus, haptic recognition memory for verbal stimuli can be better than that for nonverbal, nonsense stimuli only if the verbal stimuli can be dually coded (verbally and spatially). The result that a laterality effect was found only for upper-case letters, which became visible only when the right hand performed the task second, suggests that laterality effects in haptic recognition are weak.

4 GENERAL DISCUSSION

The series of studies in this thesis investigated haptic performance in terms of discrimination and recognition memory for verbal and nonverbal shapes. Verbal shapes were upper-case letters in Study 1 and upper and lower-case letters in Studies 2 and 3. The nonverbal shapes in all studies were unfamiliar nonsense shapes.

Laterality effects for letters and nonsense shapes will be addressed in the first part of the discussion. In the second part, the focus is on haptic memory performance in terms of duration of the haptic traces, as well as haptic memory capacity for letters and nonsense shapes. The discussion ends with suggestions for future research.

The results from the current studies are explained within the general framework of the Dual Coding Theory (DCT) proposed by Paivio (1991, 2007,- for a review) and the model for letter processing in vision (Madec, 2015). According to the dual coding theory there are two distinctive cognitive processing systems: one specialised for representation and processing of verbal (language related) material and the other for nonverbal (spatial, imagery) information. Both systems work independently but in cooperation, so that when certain material is encoded dually with both codes, verbal and nonverbal, that material is recognised and remembered better. An important part of the verbal system is the processing of letters.

In vision, a letter processing model based on four hierarchical and interactive processing levels has been proposed (Madec, 2015). The first level is related to perception and processing of the elementary sensory features of the stimuli. At the second level, a template representation of the letter is produced. The processing at the third level becomes independent of specific letter features like font and size, and thus becomes more abstract and shape-invariant. The fourth and final level refers to phonological processing, when the letter is coded by its name. This thesis presents a new proposal that the differentiation between verbal versus nonverbal processing in the DCT takes place mainly at the abstract and phonological stages of the letter processing model.

4.1 LATERALITY

Overall, the present results suggest that haptic laterality is rather weak. However, some laterality effects were found in all studies even though the well-known laterality effect in terms of verbal-nonverbal differentiation of hand/hemisphere advantage emerged mainly in Study 2. In that study, a clear advantage of left hand/right hemisphere in nonsense shapes discrimination was found together with a trend towards right hand/left hemisphere advantage for upper-case letters discrimination. In Studies 1 and 3, laterality effects appeared mainly in relation to memory retention. In Study 1, the haptic discrimination by left hand/right hemisphere was maintained for up to 15 s while right hand/left hemisphere performance declined progressively over increased retentions from 5 to 30 s, regardless of stimulus type. In Study 3, the right hand/left hemisphere had an advantage with upper-case letters when it performed the task second (after the left hand).

4.1.1 UPPER-CASE LETTERS

According to the laterality hypothesis, right hand/left hemisphere advantage was expected with upper-case letters. There was no such effect in Study 1. In Study 2, a marginally significant trend for expected advantage was found. In Study 3, a clear right hand/left hemisphere advantage was found.

The right hand/left hemisphere advantage for upper-case letters in Study 3 emerged only when the right hand performed the experimental blocks after the left hand. This is in agreement with a similar finding by Oscar-Berman et al. (1978), where a right hand advantage was found for recognition of upper-case letters when the right hand was the second to respond. These findings might reflect differences in the capabilities of the hemispheres to retain and transfer information to the other hemisphere. The current result suggests that the left hand/right hemisphere retains and consequently transfers haptic information to the right hand/left hemisphere better than the other way around. This is consistent with the laterality effect from Study 1, where the left hand/right hemisphere sustained its performance for up to 15 s, whereas the right hand/left hemisphere declined in performance throughout all retention times (5-30s). It might be that the memory traces in the left hemisphere fade more quickly compared to those in the right. Thus, if the right hand/left hemisphere is used first, the traces become weaker at longer intervals and consequently less information is transferred to the left hand/right hemisphere. In contrast, if the left hand/right hemisphere is used first, the memory traces are retained longer, and more information is transferred to the second right hand/left hemisphere. Therefore, subsequent performance by the right hand/left hemisphere is better than when the left hand performs first than when the right hand performs first.

Another reason for why the expected verbal advantage did not emerge when the right hand performed the task first might be related to the hypothesis that letters in haptics are initially processed spatially before verbal coding (Easton, Srinivas, & Greene, 1997; Witelson, 1974). Because letters are not usually perceived haptically, they are unfamiliar stimuli in haptics and might have invoked mainly spatial processing when the right hand first performed with them. In addition, the brief exploration time might have contributed to this by restricting the processing to mainly spatial, without enough time to reach verbal coding. Thus, when the letters were first perceived with the right hand (left hemisphere) verbal processing was not fully invoked. However, when the letters were first perceived with the left hand they were better spatially encoded by the right hemisphere. This made them spatially more familiar and in subsequent performance with the right hand (left hemisphere) it was already possible to invoke verbal coding and thus the advantage of the left hemisphere.

A weaker effect was found with the discrimination of upper-case letters in Study 2, where the right hand/left hemisphere showed a near-significant trend for better performance than the left hand/right hemisphere. These findings can again be interpreted in support of the hypothesis that letters are processed first as spatial stimuli in haptics (Witelson, 1974). Thus, participants may have relied on the initial spatial encoding to a greater extent, which may have reduced the verbal effect. The reason for this might also be related to the fact that letters are mainly visual stimuli, and they are usually not perceived through haptics. Therefore, there is no well-established tactile representation for letters. Also, while letters in vision are perceived quickly and processed partially simultaneously, letters in haptics are perceived and processed mainly in a serial manner. Consequently, a sequence of different spatial features of a letter shape has to be integrated into one object configuration before it can be recognised as a letter. This can be a more challenging task and the process takes longer time in haptics than in vision.

4.1.2 LOWER-CASE LETTERS

Lower-case letters did not show any laterality effects in either Study 2 or 3. This was contrary to the hypothesis that, due to their verbal nature, lower-case letters would invoke a right hand /left hemisphere advantage. In Study 2 we investigated haptic discrimination for upper- and lower-case letters and nonsense shapes. In Study 3 we examined recognition memory for upper- and lower-case letters and nonsense shapes. Interestingly, in both Studies 2 and 3 were found verbal laterality effects for upper-case letters (as discussed in previous section) but not for lower-case letters. A possible explanation for these results can be referred to the more complex features of lower-case letters, which were probably processed more spatially than the upper-case letters. The greater complexity of the lower-case letters probably imposed greater challenges in recognising and processing them as verbal stimuli. The right hand/left hemisphere probably did not process them as strongly as verbal shapes and this has inhibited the verbal advantage. It might have been necessary to involve greater spatial processing in the right hemisphere initially in order to recognise the more complex/difficult shape of the lower-case letters. As a consequence, both hemispheres made approximately equal contributions, and this has resulted in a lack of laterality trend/effect for lower-case letters.

Some visual studies have found a left hand/right hemisphere advantage for verbal material when the material was difficult or novel (Bradshaw & Nettleton, 1983; Mildner, 2007; Polich, 1978). This right-hemisphere advantage is explained by the contribution of the right hemisphere in pre-processing of the difficult shape prior to recognising it as verbal. For example, visually perceived masked letters invoked right hemisphere advantage while the same letters unmasked invoked left hemisphere advantage (Polich, 1978). Also, a right hemisphere advantage was found for letters with rounded versus straight lines (Pentcheva, Velichkova & Lalova, 1999). In a review on hemispheric asymmetries, Bradshaw et al. (1983) concluded that a right visual field/left hemisphere advantage tends to occur for simpler shapes, while a left visual field/right hemisphere advantage is linked to more complex shapes. In this manner, the upper-case letters had simpler shapes (straighter, simpler lines) than the lower-case letters, which helped them to be recognised more quickly as verbal shapes and this invoked stronger verbal processing by the left hemisphere. However, the verbal laterality effect for upper-case letters in Study 2 was a weak effect, probably due to the spatial contribution by the right hemisphere, though this was not as strong as with the more complex lower-case letters. Altogether, these findings suggest that laterality effects can be influenced not only by the verbal/nonverbal nature of stimuli but also by the complexity of the shapes.

4.1.3 NONSENSE SHAPES

Left hand/right hemisphere advantage was found in the haptic discrimination of nonsense shapes (Study 2). This provides further support for the claim that laterality in haptics is most often found for nonverbal stimuli and it is on the side of left hand-right hemisphere (Fagot & Lacreuse, 1997; Summers and Lederman, 1990). However, such a laterality effect was not found in Studies 1 and 3.

In Study 1, the reason for the lack of hand/hemisphere advantage for nonsense shapes might be the high number of repetitions in the experimental trials. There were 6 shapes per stimulus type combined, so that they composed 30 same and 30 different pairs for one experimental block, which was run 6 times (three retentions x both hands). Therefore, the nonsense shapes (as well as the other two stimulus types) were encountered repeatedly in a high number of trials. This allowed for the nonsense shapes to be learnt so that a verbal strategy (naming) may have been employed as well. This might also have involved verbal processing for nonsense shapes, equating the processing distribution between the hemispheres.

The expected spatial laterality effect (left-hand advantage) did not emerge for the nonsense shapes in the haptic recognition memory task (Study 3). Memory performance was very poor with the nonsense shapes in this study. This might be at least partly because the short exploration time did not allow for the shape to be fully encoded at all processing levels. That is, if we generalise the letter processing model (Madec, 2015) to also shape perception in general, we can link the current results to the four processing stages of this model. It can be assumed that, due to the short exploration time, the nonsense shapes might have been processed on the first level, where elementary features of stimuli are processed, and the second level, where a template representation is formed, may not always have been reached. Thus, their processing probably did not reach the later third and fourth levels of object processing, which we suggest entail the verbal/nonverbal systems. Thus, we suggest that no laterality effect emerged because processing took place at early sensory stages.

4.1.4 LATERALITY EFFECT IN RETENTION TIME REGARDLESS OF STIMULUS TYPE

In Study 1, regardless of stimulus type, the left hand maintained its level of performance for up to 15 s while right hand performance declined progressively throughout the retentions (5, 15, and 30 s). That suggests that the left hand/right hemisphere retained haptic shapes longer than the right hand/left hemisphere. This right hemisphere advantage is similar to that found in visual studies (Evans & Federmeier 2007; Federmeier & Benjamin, 2005; Oliveira et al., 2013). For example, in continuous recognition of words at nine lags (1, 2, 3, 5, 7,10, 20, 30, and 50 intervening words), a right hemisphere advantage was found only for the longer lags (20-50 intervening words) (Evans & Federmeier 2007). In another study with a similar task, the right hemisphere advantage emerged for concrete versus abstract words only at the long lag of 50 words (Kuper & Zimmer, 2015). Also, in a split brain study, better performance for the right hemisphere than the left was found in an old/new visual recognition task for faces, abstract images and words (reference). Altogether, this evidence supports the view that information which is predominantly processed by the right hemisphere can be retained longer.

4.1.5 LATERALITY, DUAL CODING THEORY AND LEVELS OF PROCESSING OF VERBAL/NONVERBAL INFORMATION

Even though both the laterality hypothesis and the Dual Coding Theory deal with the processing of verbal versus nonverbal information, these two theories have developed independently of each other. However, in this thesis we suggest that they could be linked so that the verbal system of the DCT is associated with predominant left hemisphere processing while the nonverbal, spatial system is linked to predominant right hemisphere processing.

Further, we suggest that the differentiation between verbal and nonverbal systems might take place at particular processing stages. Thus, we can link the DCT to the letter processing model suggested by Madec (2015). We also assume that similar levels of processing take place in vision and haptics. We thus suggest that laterality emerges at the last two levels of processing, the abstract and phonological one. The first two levels are related to extracting the elementary spatial features of the stimulus and forming a template. The laterality differences would not occur on these first sensory processing levels. A similar idea has previously been presented in laterality research, proposing that laterality differences are not usually found at early sensory stages of the experimental tasks, but they emerge mainly at the post-sensory stages, where higher cognitive demands are imposed (Summers & Lederman, 1991; Moskovitch, 1978).

4.1.6 SUMMARY OF LATERALITY EFFECTS

The present studies showed only weak haptic laterality effects. The well-known verbal laterality effect thus seems to be less pronounced in haptics than has been found in vision. This is probably because letters are mainly visual stimuli and there are no well-established haptic representations for them. Thus, they might first invoke spatial processing from the right hemisphere prior to their verbal encoding, which reduces or eliminates the verbal laterality effect. Moreover, increasing the complexity of letter shapes can invoke even stronger right hemisphere processing, reducing the left hemisphere advantage further. Also, regardless of stimulus type, the left hand/right hemisphere retained haptic information for at least 15 s while right hand/left hemisphere performance declined steadily with increasing retention time.

4.2 HAPTIC MEMORY

In this section, haptic memory performance is discussed independent of laterality effects. First the results regarding the duration of the haptic memory traces are discussed, and then the differences between the stimulus types in haptic discrimination and haptic recognition memory performance.

4.2.1 DURATION OF HAPTIC MEMORY TRACES

Study 1 investigated haptic discrimination for upper-case letters and nonsense shapes at three retention intervals of 5, 15, and 30 s. The results showed that the general level of performance across stimulus types and exploration hand was sustained for up to 15 s. That is, performance at 30 s retentions was significantly worse than at 15 and at 5 s retention intervals. This agrees with similar findings in the study by Kiphart et al. (1992) where discrimination performance (d’) for three-dimensional nonsense shapes was sustained between 5 and 15 s retention intervals and declined at 30 s. Also, a similar finding for sustained high discrimination performance for up to 20 s was found for geometrical shapes (Bowers et al., 1990). However, in a study of Woods et al. (2004) discrimination of nonverbal shapes was significantly worse at 15 and 30 s retentions than at 0 seconds. It is worth noting that this rapidly declining memory performance was mainly derived by the experimental conditions, under which the stimuli were highly similar in shape, which eventually imposed greater task challenges. That is, stimulus shapes varied on the x and y axis and some of the shapes were quite similar on these two dimensions while others were different. The effect of retention time was not found when the stimuli were highly discriminable (varied highly on both x and y axis).

The current result for duration of the haptic traces from Study 1 can be further compared with other memory tactile studies that used stimuli other than haptic shapes. Memory performance is sustained without deterioration for up to 10 s in orientation matching task (Kaas et al., 2007). Localisation of touch was also sustained up to 10 s and deteriorated gradually at longer retentions of up to 60 s (Gilson and Baddeley, 1969). In a task involving discrimination of orientation of grating stimuli, performance declined for up to 15 s and after that it was sustained at the same level between 15 and 30 s (Yu et al., 2013). Sinclair, Kuo, & Burton (2000) found that the first sensory memory stage for discrimination of vibrotactile stimuli lasted for up to 5 s while the next memory stage when performance was influenced by rehearsals and interference lasted for up to 30 s. Coming back to the current results (Study 1) for maintained accuracy between 5 and 15 s, it can be assumed that this sustained memory performance was due to rehearsal strategies (i.e., naming). That is, after a high number of repetitions (included in the study design) the participants were able to name many of the stimuli. Thus, the retentions between 5 and 15 s in Study 1 might have responded to the sensory memory stage, when the haptic memory is improved by rehearsal. This might indirectly suggest that the early sensory memory stage in the current task probably takes place in the first time interval of about 5 s. In this way, the results from Study 1 would agree with the suggested interval range for sensory tactile/haptic memory store of approximately 5 s (Millar, 1974; Kaas et al., 2007, Sinclair at al., 1996, 2000). Altogether, these findings suggest that the duration of the haptic memory traces is probably around 15 s, depending on the specific features of the stimulus and the experimental conditions.

4.2.2 MEMORY CAPACITY FOR LETTERS AND NONSENSE SHAPES

In Study 3 upper-case letters invoked the best recognition memory performance, better than lower-case letters and nonsense shapes. This is in line with the result from Study 1, where across all retentions the upper-case letters were better discriminated than the nonsense shapes. In Study 3, recognition memory performance was free from bias and thus it is possible to discuss the results in terms of memory capacity. One explanation for the better memory capacity with upper-case letters compared to nonsense shapes can be offered by the DCT (Paivio, 1991, 2007), according to which better memory performance is expected when a stimulus is encoded both verbally and spatially. The better memory capacity with upper-case letters may be due to dual coding, which facilitated performance with this stimulus type.

However, in Study 3 dual coding was also expected to enhance memory for lower-case letters compared to the nonsense shapes, but recognition memory did not differ between these two stimulus types. This result may be explained by the different stimulus complexity between the two letter types. Better performance for upper-case letters may have been due to their less complex shapes, which facilitated verbal encoding, while the more complex lower-case letters were probably encoded as mainly spatial stimuli and verbal encoding was not fully achieved. The combination of the complexity of the lower-case shapes and the short time in perceiving them perhaps prevented the participants from processing these shapes as letters. In this regard, we can refer to the hierarchy model of letter processing in vision (Madec, 2015) and deduce that similar processes might be at work for haptics as well. Thus, we can conclude that the lower-case letters were probably processed mainly at the first sensory stages without reaching the later stages of processing, when letters are associated and recognised by their names.

In general, the results from Study 3 showed poor memory capacity for all stimulus types. It was surprising that familiar letters (even though mainly in vision) showed poor memory capacity of overall 8-9 shapes remembered out of 13. However, this is in line with Bliss & Hämäläinen (2005), who found that working memory capacity for letters was poorer for touch than for vision. This might be related to the specificity of the haptic system, which processes the shapes in a sequential and thus slower way compared to vision where stimuli are perceived simultaneously and rapidly. Also, sighted people would normally lack haptic experience with letters as they would mainly be visually familiar with them.

Overall, the result for poor haptic memory capacity from Study 3 contrasts with the results for almost perfect haptic memory capacity for familiar everyday objects (Hutmacher & Kuhbandner, 2018; Klatzky et al., 1985). This can be related to the familiarity of the stimulus shape. For instance, better memory capacity has been found for familiar real objects compared to nonsense shapes (Ballesteros et al., 2005; Craddock & Lawson, 2008). In Study 3, based on the familiarity of letters and expected dual coding for them, a high memory capacity for letter shapes was predicted. However, this hypothesis was not entirely confirmed, perhaps because letters are familiar shapes within the visual domain and their familiarity is reduced if they are only perceived through touch. Further, very good memory capacity for everyday objects may stem from the rich material information which these objects provide for the haptic sense. That is, the haptic system benefits greatly from material cues of stimuli such as texture, weight, hardness and temperature (Gibson, 1966). In Study 3, due to the aim to examine haptic memory for stimuli which vary only in verbal dimension and complexity of shape, all variations of material cues were excluded. This resulted in reduced memory cues and thus a low capacity. Further, another factor that may have contributed to the overall poor memory is the 2D planar design of the stimulus shapes. Even familiar everyday objects are poorly recognised if they are presented in a 2D format (Lederman et al., 1990; Magee & Kennedy, 1980). Two-dimensional shapes impose restrictions on the haptic system as they provide information mainly about the shape contour while the three-dimensional shapes supply richer information (Lederman et al., 1990). The haptic system is most effective with 3D perception. Altogether, the lack of tactual familiarity and material cues as well as 2D planar design of stimulus shapes seem to be among the main factors contributing to the overall poor memory capacity in Study 3.

4.3 FUTURE DIRECTIONS

Further clarifying the role of stimulus familiarity in haptic memory would be an interesting research question for future study. The nonsense shapes in the current thesis represented unfamiliar stimuli, while letter shapes were haptically unfamiliar but familiar by name and visual experience. It was surprising how poor the recognition memory was with the letter shapes despite their visual familiarity. Familiarity can be examined by comparing haptic recognition memory for letters and nonsense shapes with familiar everyday objects. Such experimental design would require the equalising of several factors between the different stimulus types, such as material, size and shape complexity. However, it should be noted that this imposes a challenge regarding familiarity, as it reduces the information provided from material cues of the everyday objects, which contributes to their familiarity. Also, familiar everyday objects presented in 2D planar format would also reduce the advantage that these shapes have for haptic recognition in their natural 3D shape.

Beyond the specific verbal/nonverbal characteristics of stimuli, the verbal versus nonverbal approach with which a certain stimulus is processed may play an important role in laterality. Thus, even a verbal stimulus can invoke a right hemisphere advantage if it is processed in a spatial way rather than in a verbal one. Similarly, a nonverbal stimulus might invoke a left hemisphere verbal advantage if it is processed verbally, for example through naming. An interesting idea for future research is to test this hypothesis by aiming to control for verbal versus nonverbal processing for both verbal and nonverbal stimuli.

Further, an important factor to be considered in future studies on haptic memory is the stimulus exploration time. In the current thesis the exploration of 1 s was quite brief. Haptic perception is primarily serial and that takes longer time than, for instance, in vision. In order to ensure the encoding of the stimuli on all processing stages, longer exploration times might be required.

5 CONCLUSIONS

The results from the present series of studies suggest that haptic laterality effects in terms of verbal versus nonverbal processing exist but are weak. Haptic laterality effects were influenced by retention intervals and hand order of the task. Haptic discrimination and haptic recognition memory for upper-case letters were better than for nonsense shapes. Also, haptic memory was poorer for letters with more complex shapes (lower-case) than letters with simpler shapes (upper-case). These findings might be due to more accessible dual (verbal and spatial) coding for upper-case letters. In conclusion, the verbal/nonverbal nature of stimuli affect haptic discrimination and memory performance but laterality effects in haptics are not robust due to the predominantly spatial nature of the haptic sense.

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