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Haptic recognition memory and lateralisation for verbal and nonverbal shapes

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ABSTRACT
Laterality effects generally refer to an advantage for verbal processing in the left hemisphere and for non-verbal processing in the right hemisphere, and are often demonstrated in memory tasks in vision and audition. In contrast, their role in haptic memory is less understood. In this study, we examined haptic recognition memory and laterality for letters and nonsense shapes. We used both upper and lower case letters, with the latter designed as more complex in shape. Participants performed a recognition memory task with the left and right hand separately. Recognition memory performance (capacity and bias-free *d′*) was higher and response times were faster for upper case letters than for lower case letters and nonsense shapes. The right hand performed best for upper case letters when it performed the task after the left hand. This right hand/left hemisphere advantage appeared for upper case letters, but not lower case letters, which also had a lower memory capacity, probably due to their more complex spatial shape. These findings suggest that verbal laterality effects in haptic memory are not very prominent, which may be due to the haptic verbal stimuli being processed mainly as spatial objects without reaching robust verbal coding into memory.

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Haptic memory

Most studies on the sensory aspects of memory processes have been conducted in vision and audition while the tactile sense has received relatively less attention. Despite the importance of somatosensation in everyday life, very little is known about the operation of tactile or haptic memory.

One approach to study memory is through the means of a recognition memory paradigm. A typical tactile/haptic recognition memory experiment starts with an encoding (or study) phase where the task is to feel and memorise numerous different target objects. This is followed by a retrieval (recall or test) phase, where the participant is presented with the old, previously presented target objects intermixed with an equal number of new objects in a random order, and the task is to indicate whether each object is new or old. Performance on such recognition memory tasks provide information about the capacity of tactile/haptic memory. Here capacity is understood as the number of studied items which has been stored and subsequently recalled correctly.

In vision, there is strong evidence to suggest that after seeing thousands of images of familiar objects and scenes, people are able to recognise them subsequently with close to perfect accuracy (e.g., Standing, 1973). This storage capacity has been shown to be relatively inferior for auditory recognition, 78% hit rate (giving $d' = 1.7$, d' being a bias-free estimate of memory performance; e.g., Macmillan & Creelman, 2005), corresponding to about 50 recalled items out of 64 familiar sounds (Cohen et al., 2009). In haptics, very high recognition memory performance has been found for familiar everyday objects (Hutmacher & Kuhbandner, 2018; Klatzky et al., 1985). For example, in the study of Hutmacher and Kuhbandner (2018), blindfolded participants felt 168 familiar objects for 10 s each in the encoding phase. In the retrieval phase, they had to identify the previously felt object from two objects, one of which was new, but both belonged to the same basic category and differed only slightly in some details (e.g., two different pens). Half of the participants performed the retrieval phase immediately after the encoding phase, while the other half performed the test after a delay of one week. Memory performance was 94% correct when tested immediately and 85% correct when tested after one week. Moreover, in a subsequent experiment where the participants were not told about the following memory test and were presented with a surprise test after one week, performance was still high at 79%. The authors concluded that in everyday life quite accurate haptic representations are stored in memory even without intentional memorising.

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The conclusion that haptic memory is capacious may be true for familiar objects, but might differ for unfamiliar nonsense stimuli, or verbal stimuli that are not usually encoded using touch. For instance, Newell et al. (2001) used unfamiliar abstract objects as stimuli. The participants haptically explored four three-dimensional (3D) abstract shapes (constructed from LEGO bricks) for 60 s in the encoding phase and had to recognise these objects from a set of eight test shapes, four of which were new in the retrieval phase. Some of the shapes were rotated 180° in x, y or z axis depending on the experimental condition in the retrieval phase. The results showed 75% correct recognition when objects were presented in the same view (0°) as during the encoding phase. This rate dropped to 60% when objects were rotated by 180° around the vertical axis. Relevant to the current study, it should be noted that performance did not reach ceiling even though only four items were encoded, suggesting that memory capacity for these complex unfamiliar objects is very poor.

There is also direct evidence that recognition memory is better for familiar objects than nonsense objects in 3–16 year-old children (Ballesteros et al., 2005). In that study, the familiar objects consisted of six real objects, whereas the nonsense stimuli were four plastic 3D shapes. Performance (hits-false alarms) with familiar objects was at ceiling for children older than about six years. In contrast, performance with nonsense shapes increased with age but did not reach a ceiling level. In adults, the hit rate in a recognition memory task is better for familiar than unfamiliar real objects (Craddock & Lawson, 2008).

However, haptic recognition of even familiar objects can be poor if those objects are presented as two-dimensional (2D) raised-line stimuli instead of 3D real objects (Lederman, Klatzky, Chataway, & Summers , 1990 ; Magee & Kennedy, 1980). In the study of Lederman et al. (1990), blindfolded sighted participants were required to feel and verbally name 22 familiar everyday objects depicted as 2D raised-line drawings. Their performance reached a recognition rate of only 33% overall. This poor performance was in high contrast with the results of a previous study, where participants recognised 100 real 3D common objects with near perfect accuracy within 1–2 s of haptic exploration (Klatzky et al., 1985). The authors argued that this is because the haptic system performs at its best when it has access to multiple cues which are usually provided by the natural 3D objects. The haptic modality is particularly well suited for assessing material properties like texture and hardness (Gibson, 1966). Thus, when 3D common objects are explored, haptics can obtain information not only about the shape and configuration of the object but also about properties such as texture, hardness, thermal properties, size and weight. In contrast, stimuli based on raised line drawings contain information about structural properties (i.e., shape) only, providing mainly planar, contour information, but do not contain information about the third dimension or material cues which can be important for the haptic system.

In regard to verbal material, Easton et al. (1997) assessed memory performance for "letters forming a word"-stimuli to measure within-modal and cross-modal priming between vision and haptics. The aim was to investigate whether the representations of verbal stimuli are distinct or shared between the two modalities. If a larger within-modal than cross-modal priming effect is found that is usually interpreted as evidence for specific modality representations. The haptic stimuli used were raised, 2.5 cm letters printed on capsule paper. Visual letters were sequentially presented on a black and white screen, i.e., each visual letter was presented for 5 s followed by 2 s delay until the presentation of the next letter. This timing was equivalent to that found in the haptic experiment in which participants took 5 s on average to read each letter forming a word using touch alone. The participants conducted a word stem completion task and a cued recall task. Performance in both tasks did not differ between vision and haptics. Thus, there was no evidence for a larger within-modal priming effect, which suggests that the verbal stimuli have shared representations across vision and haptics. The authors suggested that at an early stage of processing, the letters and words might be represented as geometric shapes before they are identified lexically. This idea has previously been proposed for the haptic encoding of letters: Witelson (1974) suggested that letters are initially represented by touch as spatial (geometric) shapes and only after that they are converted into a verbal code. This processing might be related to the fact that letters are mainly visual stimuli and individuals do not usually have experience with perceiving letters through touch. Thus, even though letters are familiar stimuli for sighted people, they are less familiar when are perceived through touch only. Interestingly, there is evidence to suggest that in cases of blindness, areas of the brain that normally process visual information can also be activated by verbal material encoded through touch suggesting shared neural resources between visual and tactile letter perception (e.g., Amedi, Raz, Pianka, Malach, & Zohary , 2003).

In a behavioural study, Bliss and Hämäläinen (2005) showed that working memory capacity was lower for haptic than visual letters. In that study, the n-back task was applied to examine working memory performance for visually and haptically perceived letters. Participants were presented with one letter at a time on a computer screen (visual) or on a plastic board (haptic), and they had to identify (through seeing/touching), and remember the order of the letters. After each letter was presented, the participant was required to respond whether it was the same as the 0-back, 1-back, 2-back or 3-back letter. Task difficulty was associated with how many steps back the comparison had to be done, with 0-back being the easiest and 3-back being the most difficult. The results showed that an increase in the difficulty level led to a decrease in memory performance in both modalitities but the decrease was larger in the haptic compared to visual modality. The authors concluded that the working memory capacity for letters is poorer in haptics than in vision.

The processing of verbal and non-verbal material is closely related to the dual coding theory (DCT), which has been developed within memory research, but has later been extended to account for cognition in general (Paivio, 2007, for a review). According to this theory, there are two independent but interconnected cognitive systems – verbal and non-verbal. The verbal system represents the external world indirectly through language symbols. The non-verbal system operates more directly and is specialised for non-language, spatial material. Even though each system has its specialisation, they work in cooperation. According to the theory, the verbal and non-verbal systems have additive effects. There is indeed evidence that stimuli are better remembered if they are dually encoded, i.e., both verbally (e.g., naming) and non-verbally (e.g., through images or spatially). The relationship between the verbal and non-verbal systems with the sensory modalities is orthogonal. That is, the input to these systems can come through different sensory modalities (vision, audition, touch) and thus, the verbal and non-verbal processing can be distinguished within each modality. Most of the research related to this theory has been done in vision and audition, while the verbal and non-verbal memory processing in touch is not yet well studied.

Additionally, rather little is known about how fast responses are made in haptic memory tasks because response times are rarely measured. It has been shown that response times are shorter for familiar real objects than unfamiliar objects in a haptic recognition memory task (Craddock & Lawson, 2008). In another study, Craddock and Lawson (2009a) found that presenting a familiar object in a different size in the retrieval phase increases response time and errors. Santaniello et al. (2018) investigated the effects of visual deprivation on haptic memory performance by comparing accuracy and timing across two groups of participants, one of which was blindfolded for two hours before the experiment and the other, the control group, was not. Participants performed a continuous haptic recognition memory task in which real objects were presented twice each with various lags (i.e., number of intervening objects) between the first and repeated presentation. Visual deprivation prior to the experiment appeared to benefit performance with faster responses to new objects by the blindfolded than the control group. Others have reported that familiar 3D objects are quickly recognised with almost perfect accuracy within about 1–2 s of haptic exploration (Klatzky et al., 1985). In our previous haptic study of the discrimination of upper and lower case letters and nonsense shapes, we measured response times for "same" and "different" pairs of stimuli explored for 1 s (Stoycheva et al., 2020). Response times did not differ between stimulus types (1.9 s on average across stimuli), but there was a laterality effect so that the left hand was faster than the right hand in responding "different" for lower case letters. Response times in haptic memory tasks for letters and nonsense shapes have not previously been reported. However, Craddock and Lawson (2009b) and Yamashita (2015) recorded response times in investigation of laterality in the haptic recognition of familiar objects. No hand advantage was found for response times or accuracy in these studies. Given the results of Stoycheva et al. (2020) however, it might be expected that laterality effects emerge between letter shapes and nonsense shapes as the verbal/nonverbal processing is more lateralised.

Lateralisation and memory

The left hemisphere typically shows a general advantage for verbal processing and the right hemisphere for non-verbal, spatial processing. In the tactile domain, information perceived through the left hand is initially processed by the right hemisphere and the right hand by the left hemisphere (Gazzaniga, 1995, 2005; Hansson & Brismar, 1999). Thus, laterality effects in haptics might emerge as differential performance between the hands and the respective hemispheres in terms of accuracy, reaction times or patterns of performance in certain tasks. For example, performance may be expected to be more accurate and faster when the right hand is used in verbal tasks, compared to the left hand. Furthermore, there is evidence from visual and haptic studies that laterality effects might become more prominent in memory tasks involving retention times (Evans & Federmeier, 2007; Millar, 1974; Oliveira et al., 2013; Oscar-Berman et al., 1978). In a previous haptic study, we aimed to examine the interaction between retention intervals and laterality in a shape discrimination task (Stoycheva & Tiippana, 2018). In that study, letters, geometrical shapes and nonsense shapes were discriminated with the right and left hand (separately) at retention intervals of 5, 15 and 30 s. Across stimulus types, the left hand sustained performance up to 15 s, while performance by the right hand progressively decreased over the retention intervals. This suggests that the left hand-right hemisphere might be less prone to forgetting over the time delay.

Neuroimaging studies on visual processing have provided evidence for cortical lateralisation between verbal and non-verbal stimuli (Esteves, Lopes, Almeida, Sousa, & Leite-Almeida, 2020- for a review), although similar studies on haptic lateralisation have yet to be conducted. These studies on visual processing have shown a left lateralisation in the prefrontal cortex during recognition of verbal stimuli and greater right activation for nonverbal stimuli (Dalton et al., 2016; Kelley et al., 1998; Wagner et al., 1998). For instance, in Kelley et al.'s (1998) study, participants performed recognition memory tasks involving visual written words, line-drawn objects and unfamiliar faces. The dorsal frontal activations were greater in the left than right hemisphere for words, and greater in the right than left hemisphere for faces. Therefore, it is possible that the two hemispheres might also be differentially involved in haptic memory processes for verbal and non-verbal shapes.

Although some behavioural studies in tactile/haptic lateralisation have focused on the verbal/nonverbal laterality effects, typically using immediate recognition tasks, none have explicitly addressed the relationship with haptic memory. Moreover, the results of studies addressing discrimination or identification have been inconsistent regarding the hand/hemisphere advantage. Whilst the left hand/right hemisphere advantage for nonverbal materials is often reported in haptics (Borgo, Semenza, & Puntin, 2004; Summers & Lederman, 1990- for a review), evidence for right hand/left hemisphere advantage for verbal materials is less forthcoming (Borgo et al., 2004; Oscar-Berman et al., 1978), with some reporting the opposite effect (O'Boyle & Murray, 1988, O'Boyle et al.,1987; Walch & Blanc-Garin, 1987). For example, O'Boyle et al. (1987) found a left hand/right hemisphere advantage in a task involving the recognition of capital letters traced on the palms of the hands. Also, for tasks with Braille letters the results are mixed: sometimes a left hand advantage is found (e.g., Rudel et al., 1977), and sometimes a right hand advantage (e.g., Millar, 1984) whereas others have found equivalent hand performance (Summers & Lederman, 1990, -for a review). Our previous study of the haptic discrimination of upper and lower case letters and nonsense shapes showed some expected lateralisation patterns, with a strong lateral effect for nonsense shapes which were better discriminated by the left hand while there was marginally better performance for upper case letters by right hand (Stoycheva et al., 2020). However, overall the results from perceptual recognition and discrimination tasks are mixed. In order to explain this pattern of mixed results, it has been suggested that in haptics, verbal stimuli are initially analysed using a spatial code for which the right hemisphere is expected to show an advantage and only after that the information is transformed into a verbal code (Witelson, 1974). Thus, findings for left hand/right hemisphere advantage for verbal material might be due to the initial stronger involvement of the right hemisphere in the spatial encoding of haptic stimuli. Indeed, haptic verbal stimuli may be mainly spatially processed with little contribution from the left hemisphere due to task constraints (e.g., time restriction). Consequently, it is possible that a strong left hand/right hemisphere advantage can arise for haptically perceived verbal stimuli. However, the contribution of the right hemisphere during spatial processing and the contribution of the left hemisphere for verbal processing may effectively cancel each other out. In that case, the processing of haptic verbal stimuli might become distributed equally between the two hemispheres leading to a lack of any lateral effect (see e.g., Craddock & Lawson, 2009a). Altogether this can account for the pattern of mixed results in haptically perceived verbal material.

Furthermore, there is evidence that the order of the responding hand can influence the emergence of lateral effects in haptics. Oscar-Berman et al. (1978) found a left hemisphere advantage for verbal stimuli (upper case letters) and right hemisphere advantage for non-verbal stimuli (lines) but only when responses were given by the hand which was in the second order position for reporting. That is, in half of the trials responses were collected first from the left hand and in other half, the responses were first collected from the right hand. Thus, the laterality effects occurred only for the hand ordered second to give a response. This brought evidence that in haptics the hand order in the task design is an important factor for effects of laterality to manifest. The authors explained the results with involvement of longer memory retention as the hand in the second order to report had to wait for the response from the first hand. They suggested that laterality effects are more likely to emerge when longer memory intervals are involved.

Altogether, these results suggest that verbal lateralisation in haptics seems to be weak and it appears only in certain tasks. However, studies investigating laterality in memory tasks are very scarce. Thus, it remains an open question how verbal materials are specifically remembered using haptics alone. We would expect that the retrieval of verbal shapes from memory would be better than the retrieval of nonsense shapes because verbal shapes are more familiar and can be encoded by their verbal name. Nevertheless, haptic memory performance for verbal stimuli may still be expected to be worse than for familiar objects which are more typically encoded by touch and provide multiple cues for retrieval within the haptic system.

The current study

In the present study, we further investigated the relationship between memory and laterality in haptics using a recognition memory paradigm. Based on previous literature, we expected to find laterality effects as the task involved relatively long retention times between the study and the retrieval phase. Furthermore, we investigated whether haptic recognition memory depends on the verbal or non-verbal nature of the stimuli. We used letters as verbal material and nonsense shapes as non-verbal material. Nonsense shapes were unfamiliar shapes consisting of a combination of curvy and straight contours. Furthermore, we used two different types of letters: upper case and lower case. This was based on our previous study (Stoycheva et al., 2020), where we found that discriminability was higher for upper than lower case letters, and we attributed this to the typography features which were more complex for lower case letters. Thus, here we aimed to examine whether recognition memory would differ between more and less complex verbal shapes.

Our first hypothesis was that haptic recognition memory would differ between the verbal and nonsense-shape stimuli. Specifically, performance with both letter shapes was expected to be better than with nonsense shapes because we expected that memory would benefit from the combined verbal and spatial code and thus form stronger memory traces. Furthermore, due to differences in the complexity of the typography used across the letter stimuli, we expected better memory performance for upper case (less complex) compared to lower case (more complex) letters.

Our second hypothesis was that there would be a right hand/left hemisphere advantage for letters and left hand/right hemisphere advantage for nonsense shapes. This prediction was based on the original laterality hypothesis that the left hemisphere has an advantage for processing verbal material and the right hemisphere for nonverbal material.

In order to test the laterality hypothesis, all participants performed the recognition memory task twice for each of the three stimulus types (upper case letters, lower case letters, nonsense shapes), first with one hand and then with the other hand in a counter-balanced, within-subjects design. Usually, recognition memory tasks are run only once per stimulus condition. However, it was crucial to compare performance across the hands to investigate laterality effects. In this design, it could be expected that performance might be better with the second hand because of a practice effect since the same task was conducted twice. It is also possible that some learning effect might arise depending on differences in memory processing between hands/hemispheres.

Our third hypothesis was that if the verbal component had a strong influence in this task, response times (RT) would be faster for letters (upper and lower case) than for nonsense shapes.

Methods

Participants

The participants were 30 right-handed adults (right-handedness score $M = 96.3\%$, $SD = 0.67$) recruited from the student population at the University of Helsinki. All participants had Finnish as their mother tongue and all were aged between 18 and 50 years old with an average age of 34 years ($SD = 8.7$). Of the total number, 18 were female. The Edinburgh handedness questionnaire was used to determine hand dominance. All participants completed self-assessment questionnaires indicating that no one had neurological, learning, memory or sensory deficits. The study received ethical approval from the University of Helsinki Review Board in the Humanities and Social and Behavioural Sciences.

Stimuli

Three types of haptic stimuli were created for use in the experiment: upper case letters, lower case letters and nonsense shapes. Each stimulus type was comprised of 26 planar shapes (Figure 1). The letters were chosen from the Latin Alphabet (according to the native language of the participants). The letters used for the encoding phase ($N = 13$) were always the same set (D, F, H, I, K, M, O, P, Q, T, V, X, Y) presented in a random order, as described in the procedure section. The nonsense shapes were created so that they were made of similar features to the letter stimuli (i.e., straight and curved lines) and were difficult to be verbalised. These shapes were originally hand crafted from clay for use in pilot experiments, and then the images of these stimuli were used as input into a 3D modelling computer programme (see below) to produce the stimuli used in the current study. The nonsense shapes were randomly labelled with the letter names. This was done for practical reasons because when running the experiment with the help of a computer, ordering the physical stimuli was made possible with letter labels, so that the randomised order was displayed on a computer screen by letter names, which were simple to display and easy for the experimenter to understand. Also, attaching small letter name labels to the corner of each stimulus platform made it easier for the experimenter to place the stimuli in the correct orientation.

The upper case letters were presented in Verdana, sans serif, non-italicised and bold font. The lower case letters were presented in Old Bookman, serif and italicised font. Some lower case letters were additionally slightly modified in order to exclude highly distinctive sharp features and to ensure that all serif elements were curved in shape. Therefore, the two types of letter stimuli differed in topography so that upper case letters constituted more straight and simpler elements while the lower case letters consisted of curvier and more intricate features. It could be noted that, due to the nature of the Latin alphabet, some letters were very similar when presented in upper and lower case (e.g., O-o, X-x) while others are quite different in shape (e.g., A-a, G-g).

All stimuli were 3D printed from grey plastic and all sized to within the approximate dimensions of 4 cm in height and 4 cm in width. All were 0.7 cm in depth. Each stimulus was glued and secured with a metal screw onto a metal-coated platform of $10 \times 10 \times 0.3$ cm with black matte finish. The 3D modelling of the stimuli was done using Autodesk Fusion 360 (San Rafael, CA, USA). 3D printing was completed with the Form 2 printer from Formlabs (Somerville, MA, USA), with standard grey resin (V4) at 100 µm resolution. The stimuli were designed with 1 mm fillet on the top edges and outer corners. The printouts were further manually modified to remove any surface artefacts which occurred during the 3D printing process.

Apparatus

During the experiment, the participant wore opaque glasses to ensure that all stimuli were occluded from view. This allowed for free movements of the eyes

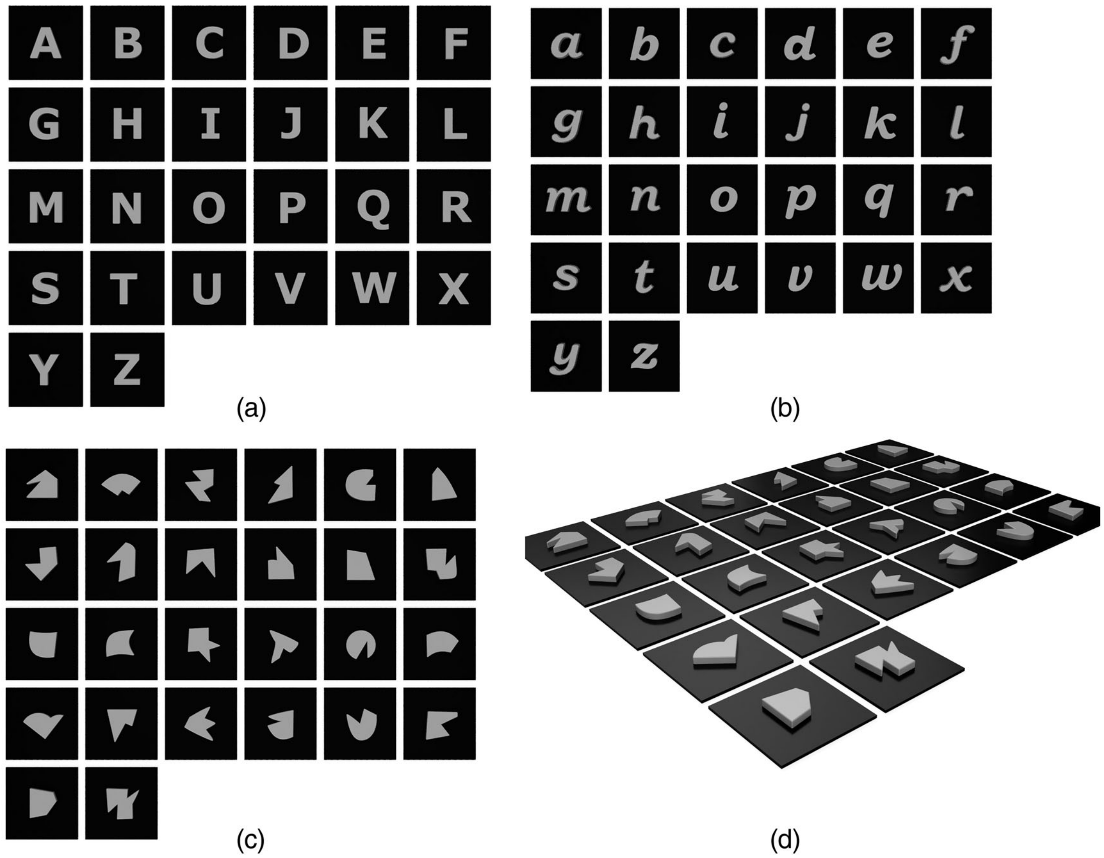

Figure 1. An illustration of the haptic stimulus set. (a) Upper case letters, (b) lower case letters, (c) nonsense shapes. (d) shows the same nonsense shapes as in (c) from a different angle to help illustrate their shapes.

without seeing the stimuli at any time during the experiment. Participants did not preview the stimuli but were told only of the type of shapes they were about to explore. Prior to testing each participant was instructed to sit comfortably on an adjustable armchair at a table so that the height of the table met the level of their elbow. The apparatus consisted of a hand pad, stimulus trays (positioned out of view) containing all the 3D pieces, a response box and desktop computer. The hand pad was positioned centrally on the table in front of the participant's body mid-line. The participant's hand rested on the table with the palm positioned downwards on the hand pad. Only one hand was used, left or right, depending on the experimental condition, and the participant was instructed to rest their other hand on the hand rail of the armchair.

Prior to each block of trials the experimenter sorted the relevant stimuli and placed those on the stimulus tray on the table. According to the presentation order of each trial/block, the experimenter placed each stimulus on the hand pad for the participant to explore and returned the stimulus to the tray after the trial. The presentation order for the stimuli in the experimental block was displayed on the computer screen visible only to the experimenter. Before the experiment started for each participant, the experimenter arranged the stimuli in the given presentation order to enable smooth changing of stimuli, keeping the correct timing. Each stimulus was oriented towards the participant and always appeared in the same upright position relative to the participant. The response box (Cedrus RB-840) was positioned centrally behind the hand pad and responses were indicated by pressing one of two response buttons. The response box was connected to a desktop computer (HP EliteDesk 800 G2) and responses were recorded with Presentation software (Neurobehavioral Systems, Albany, CA, USA). The cue sounds for timing were played through high-quality speakers (Genelec 6010A, Iisalmi, Finland), audible for both the experimenter and the participant.

Design

The experiment was based on fully factorial, mixed design, with stimulus type (upper case letters, lower case letters, nonsense shapes) and exploration hand (left, right) as within-subjects factors, and the starting hand (left, right) as a between-subjects variable. The starting hand refers to the hand used to explore the stimuli first. The experiment consisted of six experimental blocks, each consisting of an old/new recognition task with an encoding phase, followed by a retrieval phase. The first three blocks presented each of the three stimulus types, and they were performed with one hand, left or right (starting hand). The latter three blocks were performed with the other hand for each stimulus type.

The order of the blocks and hand exploration was counterbalanced across the participants. Thus, half of the participants performed the first three blocks starting with their left hand (i.e., upper case-left, lower case-left and nonsense-left) and after a break of about 15 min they performed the same blocks with their right hand. The other half of the participants started the experiment using their right hand. There were six possible orders of the stimulus types across blocks, and participants were randomly allocated to each order (i.e., four participants were presented with one of the block orders). The orders were: Upper–Lower-Nonsense; Upper-Nonsense-Lower; Lower–Upper-Nonsense; Nonsense-Upper–Lower; Nonsense-Lower–Upper and Lower-Nonsense-Upper.

Procedure

An old/new recognition memory paradigm was used. Thus, each experimental block started with an encoding phase of target stimuli (a total of 13) followed by a retrieval phase (with a total of 26 stimuli). The stimulus exploration time was always 1 s. The onset and offset of the exploration time were controlled with a computer timing programme and signalled by a click-like sound (55 dB). The same hand was always used to explore the stimuli in the encoding and retrieval phase of each block.

During the encoding phase of each block, the participant was presented with a sequence of 13 stimuli to memorise. These 13 stimuli were pseudo-randomly selected by a computer programme from the larger pool of 26 letters. The set of 13 stimuli was same for all participants but the order of the stimuli was randomised by a computer programme for each participant. All stimuli were used equally often across the experiment and the allocation of stimuli to each block was the same across participants. During the encoding phase, each stimulus was presented 5 s after the previous one. After all of the 13 stimuli were explored in the encoding phase, there was a break of around 2 min while the experimenter arranged the stimuli for the retrieval phase. Immediately after this pause, the retrieval phase started.

During the retrieval phase of each block, the 13 target stimuli and 13 new distractor stimuli were presented in succession and in a random order across participants. The participant gave a response to each stimulus as to whether it was old (i.e., a target stimulus explored in the encoding phase) or whether it was a new one by pressing the left or right button on the response box, respectively. Accuracy was emphasised over speed. Thus, participants were told that they could answer as soon as they were ready, but they can have few seconds if needed. During this retrieval phase, each stimulus was presented 5 s after a response to the previous stimulus was given.

Before the actual experiment, a practice session was conducted to ensure that the participant had understood the experimental task. For practice we used a different stimulus set (geometrical shapes) which was not included in the experiment.

Prior to the start of each trial, the participant held their hand above the hand pad, ready to explore, until they heard the click sounds which indicated to begin exploring the stimulus. The participant finished exploring the stimulus by lifting their hand up as soon as they heard the second (different) click sound. Participants quickly learned the timing and sequence of these events during the practice session.

Data analyses

Haptic memory performance was expressed in terms of discriminability d' and criterion c from the signal detection theory (Macmillan & Creelman, 2005), as well as response times to each trial. In the recognition memory paradigm, the discriminability index d' reflects the participant's ability to discriminate between two stimulus classes: "old" and "new", with higher values of d' indicating better memory performance. The criterion c indicates whether there was a bias in the responses, for example, if the participant favoured one response over the other ("old" or "new").

The correct responses were hits and correct rejections and they were defined as follows: A hit occurred when the participant responded "old" to a target stimulus presented during the encoding phase (old-old) and a correct rejection occurred when the participant responded "new" to a stimulus which had not been presented previously in the encoding phase (new-new). In contrast, incorrect responses were false alarms and misses. A false alarm occurred when the participant responded "old" to a stimulus which had not been presented during the encoding phase (new-old) and a miss occurred when the participant responded "new" to target stimulus which has been presented in the encoding phase (old-new).

To calculate d' and c according to the signal detection theory, the values of hits (Hit) and false alarms (FA) were transformed into z-values. The discriminability index d' was calculated by the formula: $d' = z(\text{Hit}) - z(\text{FA})$ and criterion c was calculated by the formula: $-0.5(z\ (\text{Hit}) + z\ (\text{FA}))$. The Hit values of 1 were adjusted with the formula $1-(1/2N)$ and FA values of 0 were substituted with the formula $1/(2N)$, where N is the number of the trials (Miller, 1996).

In order to test for differences between stimulus types, as well as to test the laterality hypothesis, separate mixed model ANOVAs for each of the d', c and response time data were conducted. The within-subject factors were stimulus type (with three levels: upper case letters, lower case letters, and nonsense shapes) and exploration hand (with two levels: left and right hand). The between-subjects variable was the starting hand (with two levels: starting with left/right hand).

With the ANOVA for *d′*, recognition memory performance for each hand and for each stimulus type was tested. Post-hoc, pairwise comparisons (with Bonferroni corrections) were subsequently applied for any interaction between hand and stimulus type. This allowed us to investigate the hypothesis that better memory performance for verbal material is associated with exploration of the right hand (left hemisphere) whereas better memory for non-verbal material is linked to exploration of the left hand (right hemisphere).

The ANOVA for *c* was conducted to investigate whether participants had a bias towards responding "old" or "new". Subsequent pairwise comparisons (with Bonferroni corrections) were applied to any interaction between hand side and stimulus type. This allowed us to compare differences between hands (i.e., hemispheres) in making an "old" or "new" decision according to different stimulus types.

The analysis of response times to the correct responses (hits and correct rejections) was also included to examine whether there was an effect of the type of correct response on reaction times. Thus, in the response time ANOVA, stimulus type (upper case letters, lower case letters, nonsense shapes), exploration hand (left and right) and correct response type (hit and correct rejection) were the within-subject factors and starting hand (left or right) was a between-subject factor.

The analyses of starting hand as a between-subjects factor were conducted because we wanted to investigate whether any effect of hand/hemisphere in memory performance was dependent on the hand order of report (which hand performed first). Furthermore, by analysing the effect of starting hand we could also determine whether the transfer of performance from one hand to the other across blocks was dependent on which hand was used first.

Results

Participants' performance in the recognition memory task for each of the stimulus types was first categorised in terms of the mean number of Hit, Correct Rejections, Misses and False alarms, as well as response times (Table 1).

Haptic memory performance (d′)

The Hits and False Alarms were used to calculate a *d′* score for each participant, which were averaged across participants. As the *d′* scores seemed to be quite low, we tested whether they differed from zero. One-sample t-tests revealed that all results for *d′* differed from zero (all $p < .01$), and thus were above chance.

The *d′* results are shown in Figure 2. The ANOVA revealed a main effect of stimulus type [$F(2,56) = 46.6$, $p < .001$, $\eta^2 = .63$] and starting hand [$F(1,28) = 5.2$, $p = .03$, $\eta^2 = .16$] but no main effect of exploration hand [$F(1,28) = 1.3$, $p = .26$, $\eta^2 = .04$]. However, the two-way interaction between exploration hand and starting hand was significant [$F(1,28) = 16.01$, $p < .001$, $\eta^2 = .36$] as was the three-way interaction between stimulus type, exploration hand and starting hand [$F(2,56) = 4.5$, $p < .02$, $\eta^2 = .14$]. The pairwise comparisons for stimulus type showed that performance to upper case letters was significantly better [mean $d' = 1.6$] than performance to either lower case letters (mean $d' = .65$; $p < .001$) or the nonsense shapes [mean $d' = .60$; $p < .001$]. There was no difference in performance between lower case letters and nonsense shapes ($p = 1$). In order to investigate the three-way interaction, we ran a separate ANOVA for each stimulus type with exploration hand and starting hand as factors. There was a significant finding only for upper case letters which was the interaction between hand and starting hand [$F(1,28) = 14.5$, $p < .01$, $\eta^2 = .34$]. Pairwise comparisons showed that performance by the right hand was significantly better than that of the left hand when the left hand was used to explore the stimuli first ($p < .01$). When the right hand was used to explore stimuli first, performance tended to be better for the left hand, but this difference did not reach significance ($p = .05$). Overall, the best performance was by the right hand when the left hand was used first, as performance in this condition was significantly better than all other hand conditions for the upper case letters (all $p < .01$).

Criterion (c)

An analysis of the *c* scores revealed a significant interaction between exploration hand and starting hand [$F(1,28) = 6.3$, $p < .02$, $\eta^2 = .19$], as shown in Figure 3, with no other main effects or interactions. The pairwise comparisons showed that when left hand performed first, the responses to exploration with the right hand had a stronger bias to respond "old" than the left hand ($p < .03$).

Haptic memory capacity

In order to determine the capacity of haptic memory for shapes, in terms of number of remembered items, we conducted an exploratory analysis of the number of hit responses made to each of the six experimental blocks. This analysis was possible since the results for criterion *c* suggested that there was no response bias for stimulus types and exploration hand overall (although there was a difference with starting hand). We also tested whether hit rates differed from zero. One sample *t* test showed that hit rates exceeded chance level (6.5) in all conditions (all $p < .01$).

Haptic memory capacity scores are shown in Table 1 (Hits). The average capacity to upper case letters was high, about 10 target shapes out of a possible 13 (9.7 and 9.8 for left and right hand, respectively). The capacity was slightly lower, about 8 to the lower case letters (8.2 and 7.8 for left and right hand, respectively), and approximately on par with the number of hits to the nonsense shapes (7.6 and 7.9 for left and right hand, respectively). In agreement with the *d′* results, ANOVA with stimulus

Table 1. (a) Performance (score out of a maximum of 13) and (b) Response time (ms) for upper and lower case letters and nonsense shapes for Hits, Correct Rejections, Misses and False Alarms. The mean and (SEM) are shown.

	Hit = Capacity		Correct rejection		Miss		False alarm	
	L	*R*	*L*	*R*	*L*	*R*	*L*	*R*
Upper case	9.7	9.8	9.9	10.2	3.3	3.2	3.1	2.8
letters	(0.5)	(0.5)	(0.4)	(0.4)	(0.5)	(0.5)	(0.4)	(0.4)
Lower case	8.2	7.8	7.9	8.2	4.8	5.2	5.1	4.8
letters	(0.3)	(0.5)	(0.4)	(0.4)	(0.3)	(0.5)	(0.4)	(0.4)
Nonsense	7.6	7.9	8.0	8.2	5.4	5.1	5.0	4.8
shapes	(0.4)	(0.4)	(0.5)	(0.5)	(0.4)	(0.4)	(0.5)	(0.5)
	Hit		Correct rejection		Miss		False alarm	
Response times	*L*	*R*	*L*	*R*	*L*	*R*	*L*	*R*
Upper case	2809	2940	2972	3221	3219	3749	3264	3615
letters	(159)	(147)	(172)	(155)	(187)	(394)	(236)	(293)
Lower case	3128	3137	3370	3447	3378	3627	3332	3282
letters	(190)	(195)	(225)	(228)	(263)	(250)	(246)	(206)
Nonsense	3087	3176	3379	3541	3464	3501	3285	3631
shapes	(198)	(181)	(219)	(243)	(234)	(230)	(250)	(265)

type and exploration hand as repeated-measures factors and starting hand as a between-subjects factor showed a main effect of stimulus type [$F(2, 56) = 21.3$, $p < .001$, $\eta^2 = .43$] and a 3-way interaction between stimulus type, exploration hand and starting hand [$F(2, 56) = 6$, $p < .006$, $\eta^2 = .18$]. In order to investigate the 3-way interaction, we conducted the same analyses as with *d′* three-way of interaction. Thus, for each stimulus type, we run ANOVA with exploration hand and starting hand as factors. There was a significant finding only for upper case letters which was the interaction between hand and starting hand [$F(1, 28) = 13.5$, $p < .01$, $\eta^2 = .33$]. Pairwise comparisons showed that the capacity of the right hand was significantly better than that of the left hand when the left hand was used to explore the stimuli first ($p < .01$).

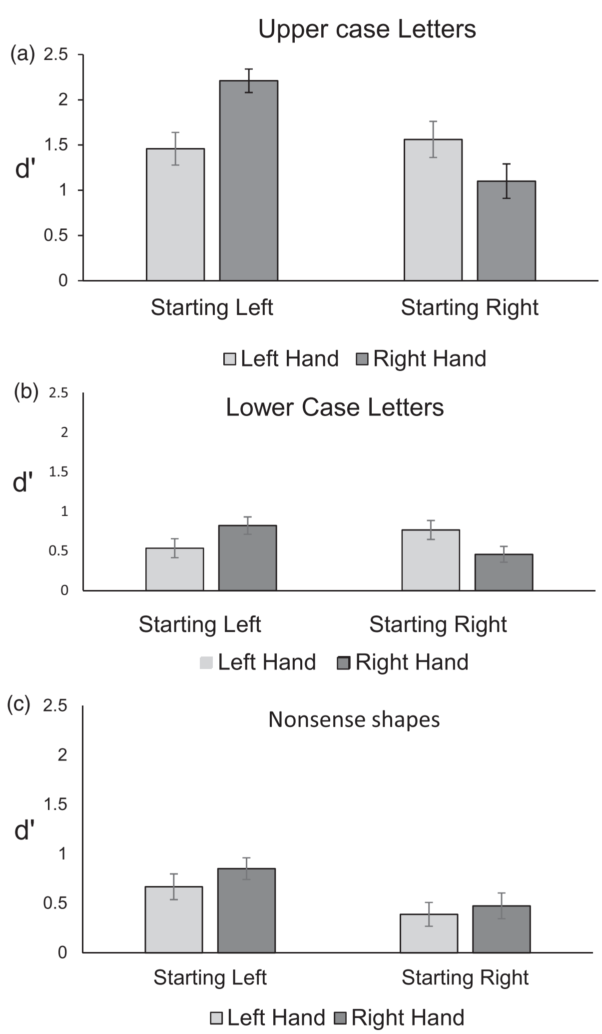

Figure 2. Haptic recognition memory performance *d′* for the left and right hand in two conditions, starting with left and starting with right hand for (a) upper case letters (b) lower case letters and (c) nonsense shapes. Error bars represent +/−1 SEM.

Response times (RT)

The analysis of the response times (Table 1(b)) yielded a main effect of stimulus type [$F(2,56) = 8.9$, $p < .003$, $\eta^2 = .24$]. Pairwise comparisons showed that the time to correctly respond to upper case letters was faster compared to either lower case letters ($p < .02$) or nonsense shapes ($p < .01$), with no evidence for a difference between lower case letters and nonsense shapes. A main effect of response type [$F(1,28) = 28.3$, $p < .001$, $\eta^2 = .50$] was also found with faster responses to hit (mean 3046 ms) than correct rejection (mean 3322 ms) responses ($p < .001$). A significant 2-way interaction between exploration hand and starting hand was found [$F(1, 28) = 10.4$, $p < .004$, $\eta^2 = .27$] as shown in Figure 4. Pairwise comparisons revealed that, across stimulus types, a response following exploration with the left hand was significantly faster than a response following exploration with the right hand but only when the experiment was started with the right hand ($p < .002$).

Discussion

Memory capacity

The current results showed a clear effect of stimulus type in a haptic recognition memory task. Memory performance

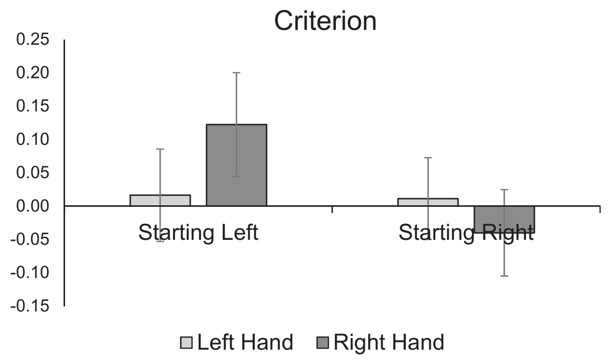

Figure 3. Response criterion *c* across stimulus types by the left and right hand for the two starting hand conditions – starting with left hand or starting with right hand. Error bars represent +/−1 SEM.

was the best for upper case letters but did not differ between lower case letters and nonsense shapes. This was the case whether the performance was expressed as *d′* or as memory capacity, i.e., the number of correctly retrieved items (although these measures are practically equivalent here due to a lack of bias in the responses). The capacity for upper case letters was relatively high, about 10 out of 13. For lower case letters and nonsense shapes the capacity was relatively lower at 8 out of 13, but above chance performance.

Overall, our results are in contrast with results of previous studies reporting haptic capacity for everyday familiar objects, specifically 168 common objects, at 94% (Hutmacher & Kuhbandner, 2018). This can be explained by the familiarity advantage which the common real objects (unlike our shapes) have as stimuli in a haptic task. For example, it has been shown that familiar real objects are remembered better than nonsense objects (Ballesteros et al., 2005; Craddock & Lawson, 2008). In our study, due to the familiarity of letter stimuli, we expected that capacity for letters would be quite high but that was not always the case. That might be because, for sighted individuals, these stimuli are familiar within the visual domain, and their familiarity diminishes when they are perceived only through touch. Another advantage of the real everyday objects is the availability of information related to the material cues of the stimuli

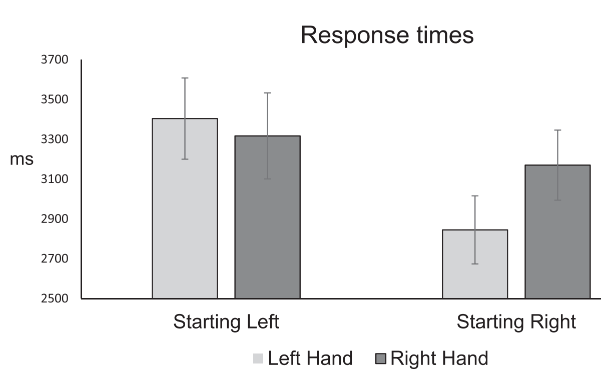

Figure 4. Participants' mean reaction times for the left and right hand used to explore the stimulus types, depending on the left or right hand used at the start of the experiment. Error bars represent +/−1 SEM.

such as texture, weight, hardness and temperature for which the haptic system is very well suited (Gibson, 1966). However, as we aimed to investigate haptic memory for shapes which vary only in the verbal dimension and complexity of shape, we had excluded any variations in material properties, which may consequently have reduced memory cues and thus capacity.

In a related study, Bliss and Hamalainen (2005) studied working memory for letters using an n-back task, and they found that memory capacity was poorer for touch than vision. This is in line with our finding of low recognition memory capacity for haptic letters.

Another factor that may have contributed to the overall low capacity in our study is that our shapes were represented in a 2D planar design. It has been shown that 2D shapes in haptics are associated with low levels of performance even for familiar objects (Lederman et al., 1990; Magee & Kennedy, 1980). The poor recognition with 2D shapes compared to 3D shapes can be accounted for by the ability of the haptic system for processing 3D shape for which it is most appropriate and effective. While the 3D shapes provide more complex information, the 2D shapes mainly provide information about the contour (Lederman et al., 1990). Altogether, these factors could explain the poor capacity performance in our study; our stimuli were lacking in both tactile familiarity and material cues, and were designed as 2D planar shapes.

Comparison between stimulus types

When comparing memory performance between different stimulus types in our study, our theoretical framework is based on the dual coding theory (Paivio, 2007), according to which performance is superior when both nonverbal and verbal encoding is involved. According to our first hypothesis, we expected that both types of letter stimuli would invoke better performance than nonsense shapes due to the possiblity to verbally encode them in addition to spatial coding. For nonsense shapes, we expected worst performance due to lack of dual coding and unfamiliarity of the shapes.

We found a higher capacity for upper case letters compared to nonsense shapes. This finding is in line with a similar result from our previous study on haptic shape discrimination where upper case letters were better discriminated than nonsense shapes (Stoycheva & Tiippana, 2018). That was interpreted as dual coding – spatial and verbal which facilitated the performance with the verbal shapes. However, in the current study and in our previous discrimination study (Stoycheva et al., 2020) we had two types of letter shapes and we expected that the verbal code would facilitate recognition for both letter shapes. Yet, this does not seem to be the case for lower case letters in the current study as they were remembered as poorly as the nonsense shapes. Interestingly, discrimination performance did not differ between these stimuli either (Stoycheva et al., 2020). Even though we presumed that letters were more familiar, being verbal stimuli, than the novel nonsense shapes, it is possible that letters are mainly familiar in the visual domain and are not usually perceived through touch. Moreover, participants could not view the stimuli at any time during the experiment and therefore visual encoding could not occur. Because of the lack of haptic familiarity, spatial complexity may then have been a determining factor over verbal encoding, resulting in similar performance between nonsense shapes and lower case letters, and superior performance for upper case letters due to their less complex shape which may facilitate verbal encoding. A similar hierarchy of processing letters, from spatial to a more abstract or verbal code, has been elucidated in the visual domain (Madec et al., 2016), therefore it is possible that similar processing can take place in haptics. Such sequential processing of letters was previously considered by Witelson (1974) who suggested that in haptics the letter stimuli are initially processed in a spatial way by their geometric features before the information to be converted verbally. A similar suggestion that letters in haptics are processed firstly as geometric shapes before being recognised as letters was also made by Easton et al. (1997).

In our study, we aimed to create verbal stimuli with the same verbal label but different spatial features, so that the lower case letters would be more complex in shape than the upper case letters. Because of this difference, recognition memory was expected to be better for the latter, as was the case. That is, the upper case letters were more likely to reach the verbal coding stage than the lower case letters. However, contrary to the DCT prediction that all letter shapes would be better memorised due to the dual code, there was no difference in memory performance between lower case letters and nonsense shapes. This suggests that both were processed mainly in the earlier spatial stages without significant contribution from verbal coding. All in all these findings suggests that a more elaborate framework than just dual coding may be needed to account for the entire pattern of findings.

It is possible that a longer exploration time could facilitate verbal coding of the higher complexity lower case letters. In a task that was not time-limited, Grundwal et al. (1999, 2001) found that more complex haptic stimuli (abstract line drawings) required longer exploration time than line drawings with simpler elements. Thus, in our task, the fixed exploration time might have been insufficient for optimal encoding, especially of the more complex lower case letters, and this may have prevented verbal identification from occurring. Consequently, it can be assumed that the lower case letters were mainly processed in a spatial manner, with no time for verbal coding. Hence, their performance remained equal to the performance with the nonsense shapes.

Lateralisation

We found a laterality effect associated with the starting hand. Specifically, for the upper case letters only, recognition memory performance was better by the right than the left hand when the left hand performed the task first. However, when the task was conducted by the right hand-left hemisphere (right hand performed first), there was a similar tendency, but the difference failed to reach significance. One explanation for this could be that when the left hand performed first, the right hemisphere processed the upper case letters as spatial stimuli rather than verbal. Subsequently, when the stimuli were explored for a second time and this time by the right hand, due to repetition the left hemisphere was already familiar with the stimuli and was therefore prepared to invoke verbal processing which this time facilitated performance.

It is interesting that the laterality effect did not emerge when the upper case letters were first explored by the right hand-left hemisphere, as predicted by the original laterality hypothesis. The reason for that might lie in that letter stimuli in haptics are initially processed spatially before being processed as a verbal code (Easton et al., 1997; Witelson, 1974). An additional factor may have been the effect of a short exploration time which might have enabled spatial rather than verbal processing. Thus, when the right hand explored the upper case letters for the first time, verbal processing was hardly invoked. Also, because letters are not tactually familiar enough their processing was mainly spatial, based on their orthographic shape. The significant advantage of the right hand (left hemisphere) was able to take place only after the upper case stimuli were perceived by the left hand (right hemisphere) first and they also become more familiar. Thus, our result is in agreement with a laterality effect which depends on hand order of response (Oscar-Berman et al., 1978), where a right hand (left hemisphere) advantage was found for upper case letters but only when the right hand was second in order to respond. The advantage in our study was evident only for upper case letters, while such an effect did not manifest for lower case letters and nonsense shapes. That might be again related to the complexity of the shape of the lower case letters which were generally processed as more spatial and thus the right hand (left hemisphere) did not process the letter stimuli as verbal stimuli.

We reached a similar conclusion in our previous study (Stoycheva et al., 2020) where the right hand (left hemisphere) discriminated the upper case letters better than lower case letters. We suggested that for lower case letters the spatial processing was stronger than the verbal one. Also, in our previous study of the discrimination of upper case letters, geometrical and nonsense shapes over 5, 15 and 30 s intervals, we found a laterality effect depending on the retention intervals across the stimulus types (Stoycheva & Tiippana, 2018). In that study the left hand (right hemisphere) sustained discrimination performance up to 15 s, while for the right hand (left hemisphere) performance progressively declined over increased retention time. We suggested that regardless of stimulus type the right hand/left hemisphere is more susceptible to forgetting. The laterality effect reported in the present study is consistent with this conclusion, i.e., better performance with the right hand for upper case letters after the left hand has performed first. Thus, if the right hand (left hemisphere) forgets more and it is used first, it transfers less information to the second left hand (right hemisphere). In contrast, if the left hand (right hemisehere) is used first, it retains more information and therefore transfers more to the second right hand (left hemisphere). However, in the current study, the forgetting of verbal information was affected, while in the previous study no dependence of stimulus type was found. This may be due to task differences. For example, in the current memory task, there was a need to remember the shapes for a longer time than in our previous discrimination task. Because of the verbal encoding of the upper case letters their decay might be slower due to dual encoding – verbal and spatial – and thus remembered for a longer time (Paivio, 2007).

There is evidence from visual fMRI studies that earlier stages of letter/word recognition are shared between both hemispheres, while at later stages information is gathered into the left hemisphere; in particular, the visual word form area (VWFA) in the left occipitotemporal cortex processes written words in a shape-invariant format, independent of e.g., letter type (Vinckier et al., 2007); even though maybe not in a fully abstract format (see Wimmer et al., 2016). We could speculate that the same processing principles would apply to the perception of haptic letter stimuli, and even that the same cortical regions might be recruited for verbal processing, as has been shown to occur in the lateral occipital cortex for visual and haptic object recognition (e.g., Lacey & Sathian, 2016, for a review). The current findings on behavioural performance could be followed up by an investigation of their neural underpinnings and whether there is evidence for shared substrates, e.g., by comparing activations in the VWFA to visually or haptically presented letters.

Response times

The response times to upper case letters were faster compared to both lower case letters and nonsense shapes. This result is consistent with our finding that memory performance was more accurate for upper case letters compared to the two other stimulus types. There are no previous haptic recognition memory studies of letters where response times were recorded, but studies on visual letter recognition are consistent with this finding. For example, Madec et al. (2016) found that the upper case letters were named more quickly than lower case letters. Also, Arditi and Cho (2007) found that a text composed only from upper case letters was read faster than text composed entirely from lower case letters or mixed case text.

Moreover, the result that response times for lower case letters and nonsense shapes did not differ supports the interpretation that these two stimulus types were processed similarly since both showed equivalent memory performance and speed of responses. That is, lower case letters and nonsense were mainly spatially encoded and the exploration time might have been too short to allow for stronger encoding, and thus the level of processing remained similar for both stimulus types. This has resulted in similar response times between lower case and nonsense shapes.

We found that hit responses (old recognised as old) were faster than correct rejection responses (new recognised as new). In line with this, Craddock and Lawson (2008) reported faster responses to old than new stimuli in a haptic recognition memory task with familiar real objects, even though they did not test for statistical significance. These results relate to a similar finding in a tactile discrimination study (Yu et al., 2013). In that study, the authors employed a discrimination paradigm with gratings, in which each stimulus was compared (same or different) to a previous one. They found faster reaction times when stimuli were matched as "same" (relatable to the "old" response in recognition task) than when they were perceived as "different" (relatable to the "new" response in recognition task). The result of faster reaction times to "same" vs "different" responses is often reported in visual research tasks (Eviatar et al., 1994; Farell, 1985,- for a review). Thus, the results of the present study and that of Yu et al. (2013) suggest that in the tactile domain also, RTs for "same" responses are faster than for "different" responses. This may reflect different mechanisms employed in the processing and decision making underlying sameness and difference responses (Jordanova & Bogdanova, 1997). Thus, making a decision of 'sameness' includes processing which is similar to a parallel comparison of multiple stimulus dimensions to a sample, while making a decision of 'different' involves the additional processing of the individual stimulus features which may prolong the processing and hence, the responding time (Jordanova & Bogdanova, 1997). However, in our previous haptic study we failed to find a clear "same" vs "different" effect in RTs although we found a laterality effect for the RTs with a faster left hand response compared to right hand for "different" pairs for lower case letters only (Stoycheva et al., 2020). We interpreted this finding as evidence for left hand/right hemisphere advantage for lower case letters which may have been processed as more spatial than verbal.

We also found a laterality effect associated with RTs, which occurred across stimulus types. The left hand responded faster than the right hand when the left hand performed second. The hand that performs as second may benefit from the practice by the previous hand and thus, the second hand may perform faster. However, we observed this effect only in one direction, so that it was not present when the left hand started and the right hand performed second. That might reflect a general advantage of the left hand/right hemisphere in being faster (independent of accuracy) with haptic perception regardless of stimulus type. This difference between the hands/hemispheres in response times might be related to the suggestion that the left hemisphere is more associated with an analytical approach while the right hemisphere is related to a more holistic or synthetic approach (Mildner, 2007, – for a review). Thus, if the left hemisphere processes all shapes more analytically, it requires sequentially analysing haptic stimulus features, and that might cause slower processing when the right hand is used. In opposite, if the right hemisphere processes haptic stimuli more holistically, it approaches them as a whole, and that might result in faster processing when the left hand is used. Further, this difference in RTs became obvious only when the left hand/right hemisphere performed second in order which supports the hypothesis for interaction between hand order of report and laterality effects in haptic.

Future directions

In the current study, the nonsense stimuli represented unfamiliar shapes while the letters were familiar as visual stimuli, and by their names, but unfamiliar in terms of haptic experience with their shapes. We found that haptic recognition memory was poor for all stimuli, including letters. In contrast, haptic recognition memory for familiar everyday objects has been shown to be close to perfect (Hutmacher & Kuhbandner, 2018; Klatzky et al., 1985). Thus, poor performance for haptic letters was surprising in light of their (visual) familiarity. In future studies, it will be interesting to clarify the contribution of familiarity in haptic recognition memory. For instance, this can be investigated through directly comparing haptic recognition memory for familiar everyday objects with letters and nonsense shapes. There are certain considerations to take into account before embarking on such a study. For example, if familiar shapes are included as stimuli in order to compare them with letters and nonsense shapes, this would require equalising several properties between stimulus types, such as material, featural complexity and size. Thus, an argument could be made that this process may affect the familiarity of the object stimuli themselves by removing some of the essential properties that make the objects familiar. Furthermore, exploration time has to be the same for all stimulus types and it is possible that familiar objects may require different timing. In the current study we used 1 s, which is very brief. An alternative approach would be to systematically increase exploration time of the stimuli for each of the stimulus types. As such, if exploration times were extended, an increase in memory performance for all stimulus types could be expected.

Conclusion

The present study showed that haptic recognition memory is influenced by the verbal/nonverbal nature of the stimuli. We hypothesised that verbal stimuli would be remembered better than nonverbal but only if the verbal stimuli can be encoded dually – spatially and verbally – in which case both ways of encoding would facilitate memory performance because of their additive effects. Further, we hypothesised that this dual coding might depend on the complexity of the stimulus shape so that spatial coding is stronger and verbal coding is weaker for more complex shapes. These hypotheses were supported since recognition memory performance was better for upper case letters than nonsense shapes and lower case letters, which were more elaborate in shape. Regarding laterality, we expected a right hand/left hemisphere advantage for letters and left hand/right hemisphere advantage for nonsense shapes. We found a laterality effect only for upper case letters and only in the condition when the right hand performed the task second in order. This suggests that laterality effects in haptic recognition memory are weak.

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References

Amedi, A., Raz, N., Pianka, P., Malach, R., & Zohary, E. (2003). Early 'visual' cortex activation correlates with superior verbal memory performance in the blind. *Nature Neuroscience*, *6*(7), 758–766. https://doi.org/10.1038/nn1072

Arditi, A., & Cho, J. (2007). Letter case and text legibility in normal and low vision. *Vision Research*, *47*(19), 2499–2505. https://doi.org/10.1016/j.visres.2007.06.010

Ballesteros, S., Bardisa, D., Millar, S., & Reales, J. M. (2005). The haptic test battery: A new instrument to test tactual abilities in blind and visually impaired and sighted children. *British Journal of Visual Impairment*, *23*(1), 11–24. https://doi.org/10.1177/0264619605051717

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. https://doi.org/10.1111/j.1467-9450.2005.00454.x

Borgo, F., Semenza, C., & Puntin, P. (2004). Hemispheric differences in dichaptic scanning of verbal and spatial material by adult males and females. *Neuropsychologia*, *42*(14), 1896–1901. https://doi.org/10.1016/j.neuropsychologia.2004.05.010

Cohen, M. A., Horowitz, T. S., & Wolfe, J. M. (2009). Auditory recognition memory is inferior to visual recognition memory. *Proceedings of the National Academy of Sciences*, *106*(14), 6008–6010. https://doi.org/10.1073/pnas.0811884106

Craddock, M., & Lawson, R. (2008). Repetition priming and the haptic recognition of familiar and unfamiliar objects. *Perception &*

Psychophysics, *70*(7), 1350–1365. https://doi.org/10.3758/PP.70.7.1350

Craddock, M., & Lawson, R. (2009a). Do left and right matter for haptic recognition of familiar objects? *Perception*, *38*(9), 1355–1376. https://doi.org/10.1068/p6312

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

Dalton, M., Hornberger, M., & Piguet, O. (2016). Material specific lateralization of medial temporal lobe function: An fMRI investigation. *Human Brain Mapping*, *37*(3), 933–941. https://doi.org/10.1002/hbm.23077

Easton, R. D., Srinivas, K., & Greene, A. J. (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*(1), 153–163. https://doi.org/10.1037/0278-7393.23.1.153

Esteves, M., Lopes, S. S., Almeida, A., Sousa, N., & Leite-Almeida, H. (2020). Unmasking the relevance of hemispheric asymmetries-break on through (to the other side). *Progress in Neurobiology*, *Sep,192*, Article 101823. https://doi.org/10.1016/j.pneurobio.2020.101823 PMID:32433927

Evans, K. M., & Federmeier, K. D. (2007). The memory that's right and the memory that's left: Event-related potentials reveal hemispheric asymmetries in the encoding and retention of verbal information. *Neuropsychologia*, *45*(8), 1777–1790. https://doi.org/10.1016/j.neuropsychologia.2006.12.014

Eviatar, Z., Zaidel, E., & Wickens, T. (1994). Nominal and physical decision criteria in same-different judgments. *Perception & Psychophysics*, *56*(1), 62–72. https://doi.org/10.3758/bf03211691

Farell, B. (1985). "Same"-"different" judgements: A review of current controversies in perceptual comparisons. *Psychological Bulletin*, *98*(3), 419–456. https://doi.org/10.1037/0033-2909.98.3.419

Gazzaniga, M. S. (1995). Principles of human brain organization derived from split-brain studies. *Neuron*, *14*(2), 217–228. https://doi.org/10.1016/0896-6273(95)90280-5

Gazzaniga, M. S. (2005). Forty-five years of split-brain research and still going strong. *Nature Reviews Neuroscience*, *6*(8), 653–659. https://doi.org/10.1038/nrn1723

Gibson, J. J. (1966). *The senses considered as perceptual systems*. George Allen & Unwin LTD.

Grundwald, M., Weiss, T., Krause, W., Beyer, L., Rost, R., Gutberlet, I., & Gertz, H. J. (1999). Power of theta waves in the EEG of human subjects increases during recall of haptic information. *Neuroscience Letters*, *260*(3), 189–192. https://doi.org/10.1016/s0304-3940(98)00990-2

Grundwald, M., Weiss, T., Krause, W., Beyer, L., Rost, R., Gutberlet, I., & Gertz, H. J. (2001). Theta power in the EEG of humans during ongoing processing in a haptic object recognition task. *Cognitive Brain Research*, *11*(1), 33–37. https://doi.org/10.1016/s0926-6410(00)00061-6

Hansson, T., & Brismar, T. (1999). Tactile stimulation of the hand causes bilateral cortical activation: A functional magnetic resonance study in humans. *Neuroscience Letters*, *271*(1), 29–32. https://doi.org/10.1016/s0304-3940(99)00508-x

Hutmacher, F., & Kuhbandner, C. (2018). Long-Term memory for haptically explored objects: Fidelity, durability, incidental encoding, and cross-modal transfer. *Psychological Science*, *29*(12), 2031–2038. https://doi.org/10.1177/0956797618803644

Jordanova, M., & Bogdanova, E. (1997). Same-different judgement and information processing in six years old children. *Bulgarian Academy of Science Journal*, 1(1), 239–249.

Kelley, W. M., Miezin, F. M., McDermott, K. B., Buckner, R. L., Raichle, M. E., Cohen, N. J., … Petersen, S. E. (1998). Hemispheric specialization in human dorsal frontal cortex and medial temporal lobe for verbal and nonverbal memory encoding. *Neuron*, *20*(5), 927–936. https://doi.org/10.1016/s0896-6273(00)80474-2

Klatzky, R. L., Lederman, S. J., & Metzger, V. A. (1985). Identifying objects by touch: An "expert system". *Perception & Psychophysics*, *37*(4), 299–302. https://doi.org/10.3758/bf03211351

Lacey, S, & Sathian, K. (2016). Crossmodal and multisensory interactions between vision and touch. In Tony J. Prescott, Eugene Izhikevich, & Ehud Ahissar (Eds.), *Scholarpedia of touch*. San Diego, USA: Atlantis Press.

Lederman, S. J, Klatzky, R. L., Chataway, C., & Summers, C. D. (1990). Visual mediation and the haptic recognition of two-dimensional pictures of common objects. *Perception & Psychophysics*, *47*(1), 54–64. https://doi.org/10.3758/BF03208164

Macmillan, N., & Creelman, C. (2005). *Detection theory: A user's guide*. Cambridge University Press.

Madec, S., Le Goff, K., Riès, S. K., Legou, T., Rousselet, G., Courrieu, P., Alario, F., Grainger, J., & Rey, A. (2016). The time course of visual influences in letter recognition. *Cognitive, Affective, & Behavioral Neuroscience*, *16*(3), 406–414. https://doi.org/10.3758/s13415-015-0400-5

Magee, L., & Kennedy, J. (1980). Exploring pictures tactually. *Nature*, *283*(5744), 287–288. https://doi.org/10.1038/283287a0

Mildner, V. (2007). *Cognitive neuroscience of human communication*. Psychology press.

Millar, S. (1974). Tactile short-term memory by blind and sighted children. *British Journal of Psychology*, *65*(2), 253–263. https://doi.org/10.1111/j.2044-8295.1974.tb01399.x

Millar, S. (1984). Is there a "best hand" for braille? *Cortex*, *20*(1), 75–87. https://doi.org/10.1016/s0010-9452(84)80025-8

Miller, J. (1996). The sampling distribution of d'. *Perception & Psychophysics*, *58*(1), 65–72. https://doi.org/10.3758/bf03205476

Newell, F. N., Ernst, M. O., Tjan, B. S., & Bulthoff, H. H. (2001). Viewpoint dependence in visual and haptic object recognition. *Psychological Science*, *12*(1), 37–42. https://doi.org/10.1111/1467-9280.00307

O'Boyle, M. W., & Murray, J. (1988). Hemispheric asymmetry in the identification of four-letter names traced in the right and left palms. *Brain and Language*, *34*(2), 294–301. https://doi.org/10.1016/0093-934X(88)90140-X

O'Boyle, M. W., Van Wyhe-Lawler, F., & Miller, D. A. (1987). Recognition of letters traced in the right and left palms: Evidence for a process-oriented tactile asymmetry. *Brain and Cognition*, *6*(4), 474–494. https://doi.org/10.1016/0278-2626(87)90141-2

Oliveira, J., Perea, M. V., Ladera, V., & Gamito, P. (2013). The roles of word concreteness and cognitive load on interhemispheric processes of recognition. *Laterality*, *18*(2), 203–215. https://doi.org/10.1080/1357650X.2011.649758

Oscar-Berman, M., Rehbein, L., Porfert, A., & Goodglass, H. (1978). Dichhaptic hand-order effects with verbal and nonverbal tactile stimulation. *Brain and Language*, *6*(3), 323–333. https://doi.org/10.1016/0093-934x(78)90066-4

Paivio, A. (2007). *Mind and its evolution: A dual coding theoretical approach*. Lawrence Erlbaum Associates.

Rudel, R., Dencku, M., & Hirsch, S. (1977). The development of left-hand superiority for discriminating braille configurations. *Neurology*, *27*(2), 160–160. https://doi.org/10.1212/WNL.27.2.160

Santaniello, G., Sebastian, M., Carretie, L., Fernandez-Folgueiras, U., & Hinojosa, J. A. (2018). Haptic recognition memory following short-term visual deprivation: Behavioral and neural correlates from ERPs and alpha band oscillations. *Biological Psychology*, *133*, 18–29. https://doi.org/10.1016/j.biopsycho.2018.01.008

Standing, L. (1973). Learning 10,000 pictures. *Quarterly Journal of Experimental Psychology*, *25*(2), 207–222. https://doi.org/10.1080/14640747308400340

Stoycheva, P. L., Kauramaki, J., Newell, F. N., & Tiippana, K. (2020). Laterality effects in the haptic discrimination of verbal and non-verbal shapes. *Laterality*, *25*(6), 654–674. https://doi.org/10.1080/1357650X.2020.1800026

Stoycheva, P., & Tiippana, K. (2018). Exploring laterality and memory effects in the haptic discrimination of verbal and non-verbal shapes. *Laterality*, *23*(6), 684–704. https://doi.org/10.1080/1357650X.2018.1450881

Summers, D. C., & Lederman, S. J. (1990). Perceptual asymmetries in the somatosensory system: A dichhaptic experiment and critical review of the literature from 1929 to 1986. *Cortex*, *26*(2), 201–226. https://doi.org/10.1016/s0010-9452(13)80351-6

Vinckier, F., Dehaene, S., Jobert, A., Dubus, J., Sigman, M., & Cohen, L. (2007). Hierarchical coding of letter strings in the ventral stream: Dissecting the inner organization of the visual word-form system. *Neuron*, *55*(1), 143–156. https://doi.org/10.1016/j.neuron.2007.05.031

Wagner, A., Poldrack, R., Eldridge, L., Desmond, J., Glover, G., & Gabrieli, J. (1998). Material-specific lateralization of prefrontal activation during episodic encoding and retrieval. *NeuroReport*, *9*(16), 3711–3717. https://doi.org/10.1097/00001756-199811160-00026

Walch, J. P., & Blanc-Garin, J. (1987). Tactual laterality effects and the processing of spatial characteristics: Dichaptic exploration of forms by first and second grade children. *Cortex*, *23*(2), 189–205. https://doi.org/10.1016/s0010-9452(87)80031-x

Wimmer, H., Ludersdorfer, P., Richlan, F., & Kronbichler, M. (2016). Visual experience shapes orthographic representations in the visual word form area. *Psychological Science*, *27*(9), 1240–1248. https://doi.org/10.1177/0956797616657319

Witelson, S. F. (1974). Hemispheric specialization for linguistic and nonlinguistic tactual perception using a dichotomous stimulation technique. *Cortex*, *10*(1), 3–17. https://doi.org/10.1016/s0010-9452(74)80034-1

Yamashita, H. (2015). Left and right hand tactile naming ability of everyday articles by a young adult sample. *International Journal of Psychological Studies*, *7*(3), 108–114. https://doi.org/10.5539/ijps.v7n3p108

Yu, Y., Yang, J., & Wu, J. (2013). Limited persistence of tactile working memory resources during delay-dependent grating orientation discrimination. *Neuroscience and Biomedical Engineering*, *1*(1), 65–72. https://doi.org/10.2174/2213385211301010011