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Exploring laterality and memory effects in the haptic discrimination of verbal and non-verbal shapes

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Abstract

The brain's left hemisphere often displays advantages in processing verbal information, while the right hemisphere favours processing non-verbal information. In the haptic domain due to contra-lateral innervations, this functional lateralization is reflected in a hand advantage during certain functions. Findings regarding the hand–hemisphere advantage for haptic information remain contradictory, however. This study addressed these laterality effects and their interaction with memory retention times in the haptic modality. Participants performed haptic discrimination of letters, geometric shapes and nonsense shapes at memory retention times of 5, 15 and 30s with the left and right hand separately, and we measured the discriminability index d'. The d' values were significantly higher for letters and geometric shapes than for nonsense shapes. This might result from dual coding (naming + spatial) or/and from a low stimulus complexity. There was no stimulus-specific laterality effect. However, we found a time-dependent laterality effect, which revealed that the performance of the left hand-right hemisphere was sustained up to 15s, while the performance of the right hand-left hemisphere decreased progressively throughout all retention times. This suggests that haptic memory traces are more robust to decay when they are processed by the left hand-right hemisphere.

Keywords: Laterality; haptic; retention; verbal; non-verbal

Introduction

The verbal–non-verbal hypothesis of functional brain lateralization

It is well known that the cerebral hemispheres are functionally distinct, each with its own unique way of contributing to cognitive processes. This is referred to as functional hemispheric asymmetry or functional brain laterality. Research on functional laterality is based on the anatomy of the sensory pathways. That is, neural pathways for most senses cross over the midline such that sensory information perceived through each visual field, ear and hand is first projected to the opposite (contra-lateral) hemisphere and each brain hemisphere has a dominant responsibility for the opposite half of the body. While in neurologically intact individuals the two hemispheres do not work independently, the differences between the hemispheres when performing certain functions can be attributed to the delayed transfer from the hemisphere that receives the information first to the hemisphere that receives the information second. Thus, if better performance in terms of accuracy or reaction time appears-for instance, by the left visual field, left ear or left hand in certain cognitive task—it is interpreted as a relative advantage of the right hemisphere for that particular cognitive function.

One of the main differentiations between the hemispheres lies along the verbal–non-verbal dimension. This refers to the way in which both hemispheres process verbal and non-verbal spatial material. Evidence for the verbal–non-verbal hypothesis stems from clinical cases as well as studies among neurologically intact individuals, which revealed a general left hemisphere advantage for processing language material and a right hemisphere superiority for processing visuospatial material or material which cannot be verbalized easily (Bradshaw, 1983; Mildner, 2008; Moscovitch, 1978 for reviews). Moreover, Bradshaw (1983) proposed that the verbal–non-verbal dichotomy could be understood as a continuum to which verbality and non-verbality represent two extremes. Similarly, Witelson (1974) suggested that stimulus material can be seen as a combination of different degrees of linguistic and spatial dimensions and that the involvement of each hemisphere when processing stimuli will depend on the components of each dimension. Thus, the stimulus properties can be distributed along this continuum and can contain different degrees of verbal and spatial elements, such that the hemispheres will process stimulus according to the components of each dimension (Bradshaw, 1983; Witelson, 1974).

Most studies on functional laterality have been conducted in the visual and auditory modality. Thus, despite the importance of it in everyday life, tactual functional laterality is less well understood. Summers and Lederman (1990) in their review of perceptual somatosensory asymmetries concluded that the patterns of hemispheric advantages in the tactile modality while less robust are generally consistent with those in the visual and auditory domains. In essence, the left hand–right hemisphere is superior for a task requiring spatial mediation and the right hand–left hemisphere is superior for a task favouring verbal mediation. Although many researchers examining tactual asymmetry agree that the laterality effects for non-verbal material primarily favour the left hand–right hemisphere, questions remain whether verbal material perceived tactually displays the traditional left hemisphere advantage (Bradshaw & Nettleton, 1983; Fagot et al., 1997; Mildner, 2008; Summers and Lederman, 1990). This stems from contradictory and inconsistent findings on the processing of verbal tactual material. Thus, at times, the traditional left hemisphere or the right hemisphere displays an advantage (see below). Still, many tasks have not displayed the expected laterality effects.

The debate on laterality effects for tactually perceived letter stimuli in neurologically intact individuals began with a study by Witelson (1974). In her dichaptic procedure, two different stimuli were presented simultaneously to the hands for tactual exploration, where upon she found an advantage in the left hand for the accurate recognition of nonsense shapes. Using the same technique, she did not find a right hand–left hemisphere superiority for tactually explored letter stimuli. Therefore, she suggested that in tasks where letters are processed tactually, letter shapes may be first analysed using a spatial code by the right hemisphere and only then the information is transformed into a language code. This provided a possible explanation for why obtaining the traditional left hemisphere advantage for verbal stimuli is more difficult. This view is also supported by tactual linguistic tasks performed by split-brain patients, where the right hemisphere shows a language capability albeit limited for tactually perceived letters (Bradshaw, 1983 for a review). Another dichaptic study by Walch and Blanc-Garin (1987) also demonstrated a left hand–right hemisphere advantage in a letter task. In this study, four letters (b, d, p, q) were used as stimuli, which were explored simultaneously (with the index finger of each hand) and subsequently identified from a visual recognition display. However, the task did not require any specific verbalization and the letters were presented simply as forms. O´Boyle at al. (1987) obtained a left hand–right hemisphere advantage for the recognition of letters traced on the palm, concluding that the physical nature superseded the language nature of the letter stimuli.

The verbal–non-verbal distinction is closely related to the dual coding theory of memory and cognition put forth by Paivio (1991; 2007). According to this theory, the verbal and non-verbal dimensions are represented symbolically through verbal and non-verbal systems, which are independent but interconnected and work in cooperation. Both classes of information (verbal and non-verbal) enter into symbolic systems through different sensory channels (visual, auditory and tactual). Thus, the verbal and non-verbal systems are multimodal and they carry additive effects. Better memory and learning are associated with dual coding verbally (through associations) and non-verbally (through images) due to the additive functions of the two systems.

Memory effects

In addition to the verbal- non- verbal factor, another factor considered in the functional laterality research focuses on the retention time between perceiving a stimulus and subsequent recognition or recall of that stimulus. This indicates whether the stimulus is processed at an early or late stage of human information processing. The early stages of information processing relate to extracting the initial low-level sensory properties of the stimulus, whereby the information is held unbiased and unaffected by rehearsal for a very short time in each modality`s sensory memory store. Later stages are related to encoding, allowing the information to be stored as a relatively stable trace, and is affected by rehearsals and cognitive transformations. Thus, at the early sensory stage in information processing, the two hemispheres are often equally good at deriving the physical features of the stimuli. Functional laterality appears mostly during the later stages of information processing (Moscovitch, 1979- for a review). Moreover, experimental tasks with longer retention times prior to the testing phase of the task demonstrated stronger asymmetry effects (Evans & Federmeier, 2007; Millar, 1974; Moscovitch, 1979 for a review; Oliveira, Perea, Ladera & Gamito, 2013; Oscar-Berman, Rehbein, Porfert & Goodglass, 1978). For instance, in Oscar-Berman et al.'s (1978) research, letters, digits and line orientations were explored dichaptically (one stimulus in each hand simultaneously) and the performance of each hand was examined. Responses were collected so that the participants reported the response for each hand in each trial. The response for the left hand was given first in order for half of the task and second in order for the other half of the task. In these conditions, a right hand–left hemisphere superiority emerged for letters and a left hand–right hemisphere superiority emerged for lines, but only for the hand that was second in order when recording the response. The responses for the second hand were thought to reflect memory processes rather than measures of initial perceptions.

Similarly, Bradshaw and Nettleton (1983) put forth a generalization that the right hemisphere advantage emerges for more complex stimuli and when longer retention intervals are involved rather than simple perceptual comparisons. Likewise, in a review of tactual laterality, Fagot, Lacreus and Vauclair (1997) concluded that tactual laterality definitively exists for complex tasks such as shape discrimination, orientation discrimination, dot patterns and the retention of sequences, favouring the left-hand side in most cases. These tasks were associated with post-sensory factors including high cognitive and memory loads. However, such laterality was not found in simple discrimination tasks, such as two-point discrimination, pressure sensitivity and point localization associated with the early sensory stages of information processing. Thus, these researchers argued that in tactual laterality experiments it is important to differentiate early sensory factors that characterize elementary tactual tasks from late post-sensory factors. They concluded that the haptic lateralization depends on the verbal–non-verbal nature of the task and on the cognitive load.

To our knowledge, the laterality effects in the haptic modality as a function of retention time have not yet been thoroughly addressed. However, some evidence exists on the laterality effects for haptic memory based on functional magnetic resonance imaging (fMRI) studies, although the laterality effects were not the focus of inquiry (Stoeckel et al., 2003; Stoeckel et al., 2004). In these studies, the cortex activation was examined using the discrimination paradigm based on the haptic exploration with the right hand of the first stimulus followed by the retention interval during which the tactile information is coded and maintained. After a retention interval of 12 to 17 s, the second stimulus was explored followed by the decision whether the stimuli were the same or different. Here, the researchers have found that during the delay stage the left prefrontal cortex (aPFC, POC) was activated and, during the actual discrimination (second stimulus) stage, the right prefrontal cortex was activated. The authors argued that the process of deliberately encoding and storing haptically perceived material is lateralized with left hemispheric predominance for maintenance and right hemispheric predominance for discrimination of haptic information. In these studies, the stimulus presentation occurred only for the right hand. However, in order to draw further conclusions on the laterality effects in haptic memory, we must examine these effects for both hands.

Hemispheric differences in memory processes have been studied primarily in the visual modality. Federmeier and Benjamin (2005) examined the processing capacity of each hemisphere for the retention of visually lateralized encoded words over time using a recognition test. Their results revealed higher hit rates and shorter reaction times in the right visual field (left hemisphere) for encoded words with short lags (2–7 intervening words), but with long lags (10–50 words) reaction times were faster for the left visual field. Using the same paradigm, a later study by Evans and Federmeier (2007) examined the time course of laterality effects by recording event-related potentials in a task consisting of the continuous recognition of centrally presented words and lateralized test words during short, medium and long repetition lags. Asymmetries emerged only for longer repetition lags (20–50 intervening words). In another study focused on word stimuli, Oliveira, Perea, Ladera and Gamito (2013) adopted a similar paradigm, and found evidence of differentiation between the hemispheres in terms of a better discrimination of concrete rather than abstract words when words were encoded in the right hemisphere and under the longest lag. In this study, this lag consisted of 50 words between encoding and the testing phase. To summarize, the results from the last three studies support the idea that the two hemispheres differ in the way they process and integrate verbal material over time. Thus, the left hemisphere is oriented towards transforming and storing verbal information at the level of abstract prototypes, thus tending towards forgetting individual features over time. The right hemisphere is more competent at encoding and retaining form-specific information and accordingly features a better opportunity to store more retrieval cues when stimulus information decays over time.

To study how memory influences laterality effects in the haptic modality, we must consider the duration of different memory stages. This stems from the assumption that laterality effects are more sound or emerge only during the later stages of information processing (after the early sensory stage). Thus, in tasks aimed at examining haptic laterality, retention times beyond the early sensory stage should be used.

Unlike the visual and auditory modalities for which sensory memory is rather well known, the duration and characteristics of tactual sensory memory are not well defined. Several studies on tactual memory using different kinds of tactual non-verbal stimuli and tasks revealed varied retention rates through which memory performance is maintained. In a study on point localization after retention intervals of 0 to 60 s, Gilson and Baddeley (1969) found that performance remained unaffected in accuracy for up to 10 s, which was interpreted as the duration of the sensory stage. Sinclair and Burton (1996) studied decay functions in a paired discrimination task using vibrotactile stimuli with inter-stimulus intervals of 0.5 to 30 s. The decay rate was fast in the first 5 s and slower for periods from 5 to 30 s. This rapid decline between 0.5 and 5 s is thought to relate to the fast decaying initial sensory memory traces after which participants relied on coded representations. However, in a review of haptic memory, Kaas, Stoeckel and Goebel (2008) suggested that the duration of the tactual sensory stage varies for various types of tactual stimuli such as vibrations, shapes and orientations, concluding that it falls within the range of 5 to 10 s.

Recently, Yu, Yang and Wu (2013) explored the effects of retention times in a haptic working memory task examining grating orientation at inter-stimulus intervals of 1, 5, 10, 15, 20, 25 and 30 s. Their study demonstrated that discrimination performance was maintained at the same level after15 s. One other study on haptic orientation matching also found a sustained performance for up to 10s (Kaas, Mier & Goebel, 2007). Experiment on haptic discrimination of non-verbal shapes applying inter-stimulus intervals of 0,5,15 and 30 s revealed better performance at 0 s compared to retention times of 15 and 30 s (Woods, O`Modhrain & Newell, 2004). Furthermore, the results from a study on the haptic discrimination of non-verbal complex LEGO blocks showed a sustained performance with delays of up to 15 s (Kiphart, Hughes, Simmons & Cross, 1992). In addition, using non-verbal but simple geometric shapes, Bowers, Mollenhauer and Luxford (1990) found a sustained high performance of up to 20-s inter-stimulus intervals.

To summarize, research on the interaction between verbal–non-verbal types of material and hand–hemisphere advantages in the tactual domain as reviewed here reveals mixed results. While some results from tactual studies support the traditional advantage of the left hemisphere for verbal stimuli, there is some evidence for opposing lateral effects. This pattern has led to the hypothesis that verbal material in the tactual domain is initially coded in a spatial tactile form for which the right hemisphere possesses an advantage. Only after that, is the information translated into a verbal code. Still, many studies did not demonstrate any lateral effects in tasks where they were expected.

Moreover, experimental evidence has suggested that increased retention intervals amplify the functional hemispheric asymmetry. Hence, the question arises whether verbal–non-verbal laterality is affected by retention time. Most of the studies on tactile memory used non-verbal stimuli and often only one hand was used for exploration, usually the right one. To our knowledge, no studies have examined the interaction between verbality and non-verbality as a function of retention time in the haptic modality.

Aims

We used a behavioural paired discrimination task in which the left and right hands separately discriminated three types of stimuli at three different memory intervals. To determine which hand–hemisphere is better at the haptic processing of verbal and non-verbal materials, we chose different types of stimuli which were intended to lie along the verbal–non-verbal continuum. We hypothesized that the verbal and non-verbal dimensions could be seen as two ends along a single continuum and the stimulus could consist of different degrees of each dimension. Accordingly, we aimed to grade our stimuli on the verbal–non-verbal scale. Thus, one stimulus type was predominantly verbal, for which we chose letters. For the second stimulus type, we chose Euclidian geometric shapes which were assumed to include both verbal and non-verbal dimensions given that these stimuli are non-verbal by nature, but with commonly accepted names. In this way, they could be easily verbalized. For the third stimulus type, we aimed to reduce the verbalization element as much as possible. Therefore, we chose nonsense shapes for which there are no clear names or labels and, thus, they are difficult to verbalize.

We had two main hypotheses. Firstly, we hypothesized that a hand advantage in terms of discrimination performance would emerge primarily for letters and for nonsense shapes because we assumed that they are extremes of the verbal–non-verbal continuum. We determined discrimination performance in terms of the discriminability index, d', of the signal detection theory (Macmillan & Creelman, 2005). A higher d' for right-hand performance for letters would supply evidence for a left-hemisphere advantage in processing verbal material in the haptic domain. In addition, we expected *d′* to be higher for left-hand performance with nonsense shapes, which would reflect a right hemisphere advantage for non-verbal, spatial material.

Secondly, since there is evidence for amplified laterality effects at longer retentions, we anticipated increasing differences in performance between the hands at longer retention times. In order to determine how retention times affect the laterality effects and the processing of verbal and non-verbal materials, we chose retention times of 5, 15 and 30 s, because haptic memory traces have been shown to begin to decay around these delays.

Methods

Participants

In total, 24 right-handed individuals (13 men, 11 women) volunteered to take part in the experiment. All participants spoke Bulgarian as their mother tongue and ranged in age from 19 to 36 (mean, 25 years). All participants were right-handed, assessed through self-report by using the Annett hand preference questionnaire. According to self-reports none of the participants had any neurological or psychiatric disease at the time of the experiment. All individuals reported normal tactile perception.

Stimuli

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; see Figure 1). We aimed to grade our three stimulus types along the verbal–non-verbal continuum. In total, we used six stimuli of each type (Figure 1). Letters consisted of A, P, X, 3, B and M. Since all participants were Bulgarian, the letters were chosen from the Bulgarian alphabet, which is a Cyrillic alphabet. Geometric shapes were chosen as non-verbal yet verbalizable forms, consisting of a triangle, circle, rectangular, square, oval and polygon. The nonsense shapes were meaningless, non-verbal figures difficult to name.

Figure 1 here:

Block structure

There were18 experimental blocks in paired discrimination task resulting from a combination of three stimulus types (letters, geometric shapes and nonsense shapes), three retention time intervals (5, 15 and 30s) and using both hands (left and right). Each block consisted of 60 trials. That is 60 stimulus pairs (30 same + 30 different). The pairs were produced in the next way: each six stimuli from same stimulus set (6 letters, 6 geometricals, 6 nonsense) received a number and were combined in pairs with each another and itself such that 30 matching (same) and 30 different pairs for each type of shape were produced. After we had our pool with 30 different and 30 same pairs, we randomized their order through lottery. This order was applied for the three stimulus sets. Even though the order was randomized only once in advance, there was no chance to memorize it because firstly, the pair list was rather long and secondly, the participants had to perform with different stimulus set each time. The retention intervals (5, 15 and 30 s) were used to block the trials. Thus, for each stimulus set there were two (one per each hand) 5-s blocks, two 15-s blocks and two 30-s blocks. The block sequence was counterbalanced in order as well as the hand use. That is, half of the participants (N=12) started the experiment with the 5-s blocks, did 15-s blocks next and finished with 30-s blocks. The other half performed in opposite order. Furthermore, these two groups were additionally divided into two halves, one of which performed the blocks with the left hand first and the other one with the right hand first. The order of stimulus type was random and not predetermined.The total duration of the experiment reached roughly 9 hours, and, depending upon the availability of participants, was performed over 3 to 5 days (average 2, 5 hours per day) with rest pauses after each experimental block.

Procedure

Participants were blindfolded and performed a sequential paired discrimination task. In this task, the haptic information perceived from one stimulus was retained for comparison with the next stimulus of the pair to yield the “same” or a “different” answer. Each participant explored the first stimulus with one hand for one second and, then after varying the retention time interval (5, 15 and 30 s) a second stimulus was explored also for one second using the same hand. As the two phases of a trial were performed by the same hand (unilateral task) we expected that the performance will predominantly reflect the processing of the contra-lateral hemisphere.

Timing was controlled using a computer program, which created the required time interval between stimuli for each of the three retention blocks (5-, 15- and 30s). The beginning and the end of each exploration phase was signalized by click. Additionally, the experimenter was monitoring the procedure and making sure that participants had the required time for exploration. The participants were familiarized with the procedure in advance.

Exploration of each stimulus through active touch with all fingers of one hand lasted for 1 s. The exploration time of 1 second was chosen in order to avoid a ceiling effect (A ceiling effect, i.e. nearly errorless performance appeared in a pilot experiment where exploration lasted 2 seconds). After the participant explored the second stimulus in the pair, s/he indicated “same” if s/he thought the two stimuli were same or “different” if s/he thought they were different. Responses were recorded manually and were given using the same hand used to explore and discriminate during that particular experimental block. Lifting the index finger indicated a response of “same” and lifting both the middle and index fingers indicated a response of “different”. The reason we used the manual response was due to the aim to restrict the task to the haptic sense and to avoid encouraging verbalization. Participants were given 10 s to respond, which began immediately after exploration of the second stimulus in the pair; a response was required even if participants were uncertain.

Data analyses

We applied the signal detection theory analysis and calculated the discriminability index d' and the criterion c (Macmillan & Creelman, 2005). The values of d' indicate how accurately the stimuli were discriminated between each other. The parameter c reflects the response bias or the tendency of the participant to favour one response over another. For calculation of hits (HIT) we chose the responses when two different stimuli were correctly discriminated as different and false alarms (FA) were the trials when two same stimuli were judged incorrectly as different. HIT and FA values were normalized to obtain the *z*-score values *z* (*HIT*) and *z* (*FA*).The d' was calculated with the formula d'= z (HIT) – z (FA) and c was calculated as c= -0.5 (z (HIT) + z (FA)). We adjusted the values of one for the hit rates with the formula 1-(1/2N), and the values of zero for false alarms by using the formula 1/(2N) where N is the number of trials (Miller, 1996).

We conducted ANOVA with d' and c values as dependent variables for repeated-measures factors ***stimulus*** (letters, geometric shapes and nonsense shapes), ***retention*** (5, 15 and 30 s) and ***hand*** (left and right). Bonferroni corrections were performed for pair-wise comparisons.

Results

The results for unilateral haptic discrimination by each hand for three types of stimuli at three retention times are presented in Table 1 in terms of discriminability d', criterion c, hits (different stimuli judged as different) and false alarms (same stimuli judged as different). Correct rejections (1- false alarms) and misses (1-hits) are not shown. Overall accuracy refers to the sum of all correct judgments, hits (different stimuli judged as different) and correct rejections (same stimuli judged as same). The analyses focus on the signal detection theory parameters d' and c, and the other variables are presented for completeness.

Discriminability d'

There was a significant main effect for stimulus type [$F\ (2, 46) = 15.7$, $p < .001$, $\eta_p^2 = .405$] in d' values as shown in Fig. 2. Paired t-tests for stimulus showed that performance with geometric shapes ($t = 7.8$, $p < .001$, $d = 0.65$) and letters ($t = 6.0$, $p < .001$, $d = 0.50$) was significantly better compared to nonsense shapes, with no difference found between letters and geometric shapes.

A main effect for retention time was also significant [$F\ (2, 46) = 8.75$, $p = .002$, $\eta_p^2 = .276$] as shown in Fig. 3a. A retention time of 30 s led to a significantly worse performance than a 5- ($t = -6.15$, $p < .001$, $d = -0.51$) and 15-s retention time ($t = -4.98$, $p < .001$, $d = -0.41$), with no difference between 5- and 15-s retention times.

The hand did not produce a significant main effect [$F\ (1, 23) = .200$, $p = .659$, $\eta_p^2 = .009$]. However, a significant interaction between hand and retention time was observed [F (2, 46) = 3.909, $p = .03$, $\eta_p^2 = .145$], but not between the hand and stimulus. The three-way interaction (stimulus * retention * hand) was not significant.

To investigate the interaction between hand and retention (Fig. 3b), further pairwise comparisons were performed. The performance of the right hand progressively deteriorated with increasing delay. That is, the right hand–left hemisphere was significantly more accurate at 5-s compared with 30-s retention time ($t = 5.14$, $p < .001$, $d = 0.61$) and compared with 15-s retention time ($t = 3.37$, $p < .001$, $d = 0.39$). Unlike the right hand, the left hand sustained the performance level between 5 and 15 s and showed a significant decrease only at 30 s compared with 15 s ($t = -4.801$, $p < .001$, $d = -0.57$).

(Table 1 about here)

Figure 2 here:

Figure 3 here:

Criterion c

ANOVA with c values showed no significant effects, except for a main effect of retention [F (2, 46) = 14.89, p< .001, η_p^2 = .552]. According to pairwise comparisons there was a significant difference between 30-s retention (c= -0.07) compared to 15-s (c=+0.02) (t=-3.3, p= .001, d=-0.3) and 5-s (c=+0.1) retention (t= -6.0, p< .001, d=-0.5). Positive values for c mean a bias towards responding “different” and negative values of c mean a bias towards responding “same”. That is, the participants had a tendency to answer more often same at 30-s than at 15- and 5-s retention.

Discussion

This study aimed to examine the hand–hemisphere advantage for verbal and non-verbal materials in the haptic modality as well as to measure the memory effects involved in haptic processing. In particular, we assessed haptic performance in discrimination task, using the left and right hands separately across three retention time intervals of 5, 15 and 30 s and for three types of stimuli- letters, geometric shapes and nonsense shapes.

We found no evidence for a double dissociation between the hand-hemisphere advantage and verbal-non-verbal stimulus type, as we found no interaction between hand and stimulus type. Our results add to previous findings which did not demonstrate verbal or non-verbal dependent laterality in the tactile modality (Fagot et al., 1993; Summers & Lederman, 1991; Witelson, 1974). For example, in relation to verbal tasks, Witelson (1974) in her haptic test did not find the traditionally predicted right hand–left hemisphere advantage in the recognition of letter pairs. As an explanation, she suggested that the verbal stimuli perceived haptically are first encoded as tactual shape patterns in the right hemisphere and, then, that information is translated into a verbal code. Thus, this inter-hemispheric transfer possibly equalized the processing distribution by each hemisphere so that there were no laterality effects. Summers and Lederman (1991) did not find hand effects in a matching-to-sample task for three-dimensional nonsense shapes, either. Moreover, the authors made a review of the literature and concluded that tactual laterality effects are inconsistent and less robust than those for vision and audition.

We found that discrimination performance of letters and geometric shapes was significantly better than that of nonsense shapes. Furthermore, letters and geometrical shapes exhibited quite similar performance. One explanation for this may be related to the coding processes. The dual coding theory states that there are two types of codes, verbal and non-verbal, which are applied for each modality: visual, auditory, and haptic (Paivio, 1991; 2007). The verbal system dominates in some tasks, while the imagery, non-verbal one is predominant in others. Even though the two systems are independent, they often work in cooperation and have additive functions to each other. Other studies in the tactile modality also brought evidence that verbal processing is involved in tactile tasks (Auvray et al., 2011; Gilson & Baddeley, 1969; Mahrer & Miles, 2002). In these studies, articulatory suppression during the interval between the stimuli led to poorer recognition compared to silence or tactile interference conditions. This suggests a verbal rehearsal strategy was used in combination with a spatial strategy in the tactile tasks. Based on these views, we assume that all of our stimulus types were initially encoded in their tactual shape pattern or image (non-verbal coding), but where possible a verbal label was applied (verbal coding).Thus, we propose that letters and geometric shapes were dually coded: non-verbally through haptic imaging and verbally through naming. One of the reasons for the poorest performance with the nonsense shapes may be the limited possibility of utilising a verbal coding strategy as there were not easily referable names for these stimulus shapes.

We aimed our stimuli to fall along a verbal–non-verbal continuum, such that our three stimulus types would consist of different levels of verbal and nonverbal elements. However, as performance on letters did not differ significantly from that for geometric shapes, our stimulus types may not lie distinctively on the verbal-non-verbal continuum as we hypothesized. It may be that letters and geometrical shapes consist of a similar combination of verbal and non-verbal elements or in other words they don't differ significantly along this dimension. In addition to the verbal–non-verbal attributes, our stimuli also may vary on other characteristics such as complexity, familiarity, meaningfulness, and concreteness and imagery values. A high correlation between concreteness, imagery value and memory exists. For example, concrete words represent concrete concepts or objects and activate two symbolic systems—the verbal and the non-verbal—while abstract words primarily activate the verbal system (Paivio, 2007). Thus, nonsense shapes can be seen as being more complex, less concrete and familiar than the letters and geometrical shapes and these may be other factors that could have contributed to the poorer performance with those stimuli. On the other hand, letters and geometrical shapes may share similar levels of complexity, concreteness and familiarity, which together with the dual coding might be an explanation for why performance with these stimuli was also quite similar.

Retention time revealed a significant main effect across stimulus types and hands. The level of performance was sustained up to 15 seconds. Furthermore, retention time did not interact with stimulus type and thus, all stimulus shapes– letters, geometrical and nonsense – maintained their performance level up to 15 s. However, performance of the hands differed significantly as a function of retention time. This was shown as retained level of performance of the left hand between 5 and 15 s, while the right hand continuously declined its performance throughout all retentions. This result highlights the importance of the counterbalanced use of both hands in studies of haptic memory. Yet, in many of the studies on tactile memory is used only one hand for exploration, usually the right one.

Our general effect of sustained performance up to 15 s across the hands and stimulus types agrees with results from Kiphart et al. (1992), who found that d' for three-dimensional nonsense shapes did not differ between 5 and 15 s but worsened at 30 s retention time. Similar, in another study for discrimination of geometrical shapes performance was consistently high throughout all retentions which were up to 20 seconds (Bowers et al., 1990). However, in contrast to our maintained performance up to 15 s, in the work of Woods et al. (2004) for three-dimensional non-verbal shapes discrimination at 15- and 30-s was significantly lower than at 0 seconds. One reason for why significant decrease appeared already at short retentions may be due to a poor stimulus discriminability. In that study the stimulus shapes varied on x and y axis which made them more or less discriminable to each other. Retention times influenced mainly the conditions when stimuli were quite similar according the two dimensions. In contrast, when the shapes were highly discriminable (varied on both x and y axis), they did not reveal an effect of retention time. This suggests that duration of haptic memory differs for the different tactual features of stimuli and variety of task demands and designs. Further, our memory effect could be compared to other memory tactile studies which used different stimuli than haptic shapes. For example, in an orientation matching task, retention times of 0.5, 5 and 10 s did not cause deterioration of performance (Kaas, Mier & Goebel, 2007). Similarly, performance was sustained up to 10 s for localisation of touch, and decreased gradually after that up to 60 s (Gilson and Baddeley, 1969). However, discrimination for orientation of gratings showed opposite of our pattern of decline – performance decreased up to 15 s but remained unchanged between 15- and 30-s retentions (Yu et al., 2013). Also, discrimination of vibrotactile stimuli decayed significantly during the first 5 s retention in a study of Sinclair and Burton (1996). In their study, this retention of 5 s is interpreted as duration of sensory memory stage, a stage for which is assumed that is not affected by rehearsal activities. It is suggested that haptic memory, similar to visual and auditory memories, is characterised by two main processes: early fast-fading sensory stage and later longer-lasting categorical stage. According to Sinclair and Burton (2000), in the early stage even though some information is lost, retaining the tactile traces is not affected by interfering (distracter) tasks and this process lasts about 5 s. In the later stage, rehearsal mechanisms can take place in order to maintain the information and this stage might last up to 30 s and longer. Based on this, we could assume that in our task the effect of sustained performance between 5 and 15 s might be due to rehearsal strategies. In this way, retentions of 5 to 15 s in our task could resemble a stage in memory processing where rehearsal strategies improve the haptic performance. Then our results would suggest that the early sensory stage in our task takes place in the first about 5 s. If so, that would agree with the range of supposed sensory tactile memory of approximately 5 s (Millar, 1974; Kaas et al., 2007, Sinclair and Burton, 1996; 2000).

A main effect of retention was the only finding in the analyses of criterion. The participants chose the response `same` more often at 30 than at 15 and 5 s intervals. It seems that at the longest retention interval of 30 s, the differences between the shapes were forgotten and the participants tended to judge the stimuli as being the same. This might be because the memory representations of the shapes became less precise with increasing retention time. This is in agreement with findings in the visual modality, where it has been shown that memory representations become noisier as retention time gets longer (Olkkonen & Allred, 2014).

Interestingly, there was a significant interaction between retention time and hand in d' values, which was due to the retained performance of the left hand for up to 15 s. In contrast, the performance of the right hand diminished gradually from 5 to 30 s. These results suggest that haptic traces stayed more robust for longer time when they were processed by left hand-right hemisphere while right hand–left hemisphere was more challenged by retention times and steadily diminished its performance.

To our knowledge, this is the first study which explores hemispheric memory asymmetries in the haptic domain for neurologically intact individuals. Our memory-related right hemisphere advantage seems consistent with time-dependent right hemisphere advantages in visual verbal tasks (Evans & Federmeier 2007; Federmeier & Benjamin, 2005).These tasks consisted of continuous recognition of words at nine levels of lags (1, 2, 3, 5, 7, 10, 20, 30, and 50 intervening words). In the time course of the tasks, right hemisphere superiority emerged only at longer repetition lags (20-50 intervening words). Using the same paradigm, there was a right hemisphere advantage for encoding concrete versus abstract words with the longest lag-50 items (Oliveira et al., 2013). One explanation for this may be that the right hemisphere encodes the information in a more concrete way while the left hemisphere encodes the information in more conceptual way (Kuper & Zimmer, 2015). Hence, the right hemisphere is more likely to remember the specific, physical form of the stimuli over longer periods of time and to make correct discriminations based on that. This hypothesis is supported also by evidence for the right hemisphere memory superiority in split brain studies (Bradshaw & Nettleton, 1983, for a review; Metcalfe et al., 1995). For example in Metcalfe`s et al. study (1995), a patient was more successful at correctly recognizing old/new stimuli in tasks for faces, abstract images and word recognition when the stimuli were presented to the right hemisphere. It seems that the information which is processed predominantly in the right hemisphere is more robust to memory decline. Thus, our finding is in line with the view that the right hemisphere advantage appears more obvious when the task includes memory demands (Bradshaw and Nettleton, 1983, Moscovitch, 1978; Oscar-Berman, 1978)

Conclusion

Our findings suggest that verbal and non-verbal components of stimulus materials remain important variables in haptic discrimination. The combination of verbal (naming) and non-verbal (spatial) coding may enhance haptic discrimination of geometrical shapes and letters, while in contrast, an increased stimulus complexity and reduced verbalization may diminish haptic discrimination for nonsense shapes. We found evidence in support of the hypothesis for laterality effects depending on retention time, as there was a difference in performance between the hands over the time delays used in our tasks. Left hand-right hemisphere performance was better in terms of sustained discrimination performance for up to 15-s retention, regardless of stimulus type, meanwhile, right hand-left hemisphere performance decreased steadily. Hence, left hand-right hemisphere seems to be less prone to forgetting perhaps because it is more likely to retain the specific form of the stimulus characteristics, resulting in more sustained haptic discrimination.

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Table 1

Means and standard errors of the means (SEM) in haptic memory discrimination task for values of a) d', b) criterion c, c) hits, d) false alarms and e) overall accuracy.

d'	Letters						Geometrical shapes						Nonsense shapes					
	5s		15s		30s		5s		15s		30s		5s		15s		30s	
	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R
mean	3,01	3,08	3,14	2,76	2,61	2,46	3,10	3,10	3,02	2,84	2,68	2,84	2,57	2,90	2,53	2,57	2,15	2,08
SEM	0,20	0,18	0,12	0,15	0,16	0,19	0,17	0,17	0,14	0,14	0,14	0,13	0,14	0,15	0,11	0,16	0,13	0,13

criterion c	Letters						Geometrical shapes						Nonsense shapes					
	5s		15s		30s		5s		15s		30s		5s		15s		30s	
	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R
mean	0,09	0,12	0,06	-0,07	-0,13	-0,17	0,05	0,11	0,02	-0,01	0,05	-0,15	0,12	0,09	0,11	0,03	-0,02	0,00
SEM	0,07	0,04	0,06	0,07	0,06	0,06	0,05	0,04	0,05	0,06	0,04	0,06	0,05	0,07	0,04	0,06	0,05	0,07

hits	Letters						Geometrical shapes						Nonsense shapes					
	5s		15s		30s		5s		15s		30s		5s		15s		30s	
	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R
mean	0,92	0,93	0,93	0,88	0,86	0,82	0,93	0,93	0,93	0,90	0,90	0,88	0,91	0,91	0,91	0,88	0,84	0,83
SEM	0,02	0,01	0,01	0,02	0,02	0,03	0,01	0,01	0,01	0,02	0,02	0,02	0,01	0,02	0,01	0,02	0,02	0,02

false alarms	Letters						Geometrical shapes						Nonsense shapes					
	5s		15s		30s		5s		15s		30s		5s		15s		30s	
	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R
mean	0,12	0,10	0,08	0,10	0,10	0,11	0,09	0,09	0,09	0,10	0,11	0,07	0,15	0,11	0,14	0,13	0,16	0,17
SEM	0,03	0,02	0,01	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,01	0,01	0,02	0,02	0,02	0,02	0,02	0,02

overall accuracy	Letters						Geometrical shapes						Nonsense shapes					
	5s		15s		30s		5s		15s		30s		5s		15s		30s	
	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R
mean	0,91	0,92	0,93	0,89	0,88	0,86	0,92	0,92	0,92	0,90	0,89	0,90	0,88	0,90	0,88	0,88	0,84	0,83
SEM	0,02	0,01	0,01	0,01	0,01	0,02	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,02	0,02

Figure captions:

Figure 1: Stimulus types: letters (a) geometrical shapes (b) and nonsense shapes (c)

Figure 2: Performance (d') in unilateral haptic memory discrimination task for three types of stimuli: Haptic discrimination for letters, geometrical shapes and nonsense shapes across retention and hands. The star indicates statistically significant (*p*<0.05) differences. Error bars denote the standard error of the mean.

Figure 3: a) Unilateral haptic discrimination at 5, 15 and 30 s retention times across stimulus types and hands. b) Unilateral haptic discrimination for each hand as a function of retention time. The stars point out statistically significant (*p*<0.05) differences. Error bars denote the standard error of the mean.

d'	Letters						Geometrical shapes						Nonsense shapes					
	5s		15s		30s		5s		15s		30s		5s		15s		30s	
	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R
mean	3.01	3.08	3.14	2.76	2.61	2.46	3.10	3.10	3.02	2.84	2.68	2.84	2.57	2.90	2.53	2.57	2.15	2.08
SEM	0.20	0.18	0.12	0.15	0.16	0.19	0.17	0.17	0.14	0.14	0.14	0.13	0.14	0.15	0.11	0.16	0.13	0.13

criterion c	Letters						Geometrical shapes						Nonsense shapes					
	5s		15s		30s		5s		15s		30s		5s		15s		30s	
	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R
mean	0.09	0.12	0.06	-0.07	-0.13	-0.17	0.05	0.11	0.02	-0.01	0.05	-0.15	0.12	0.09	0.11	0.03	-0.02	0.00
SEM	0.07	0.04	0.06	0.07	0.06	0.06	0.05	0.04	0.05	0.06	0.04	0.06	0.05	0.07	0.04	0.06	0.05	0.07

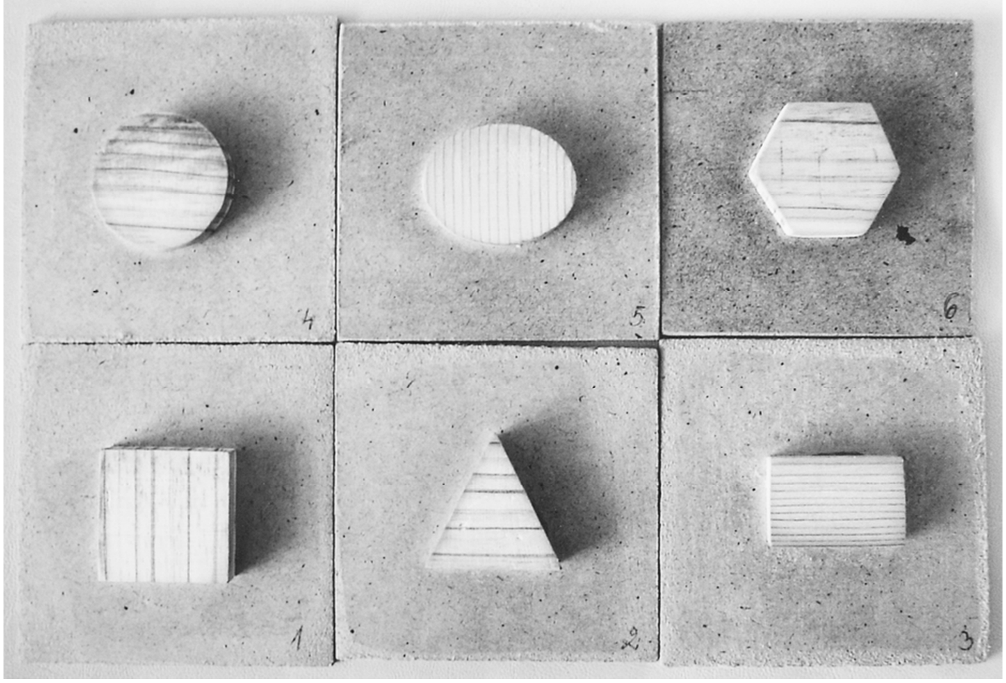
hits	Letters						Geometrical shapes						Nonsense shapes					
	5s		15s		30s		5s		15s		30s		5s		15s		30s	
	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R
mean	0.92	0.93	0.93	0.88	0.86	0.82	0.93	0.93	0.93	0.90	0.90	0.88	0.91	0.91	0.91	0.88	0.84	0.83
SEM	0.02	0.01	0.01	0.02	0.02	0.03	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.02	0.01	0.02	0.02	0.02

false alarms	Letters						Geometrical shapes						Nonsense shapes					
	5s		15s		30s		5s		15s		30s		5s		15s		30s	
	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R
mean	0.12	0.10	0.08	0.10	0.10	0.11	0.09	0.09	0.09	0.10	0.11	0.07	0.15	0.11	0.14	0.13	0.16	0.17
SEM	0.03	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02

overall accuracy	Letters						Geometrical shapes						Nonsense shapes					
	5s		15s		30s		5s		15s		30s		5s		15s		30s	
	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R
mean	0.91	0.92	0.93	0.89	0.88	0.86	0.92	0.92	0.92	0.90	0.89	0.90	0.88	0.90	0.88	0.88	0.84	0.83
SEM	0.02	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02

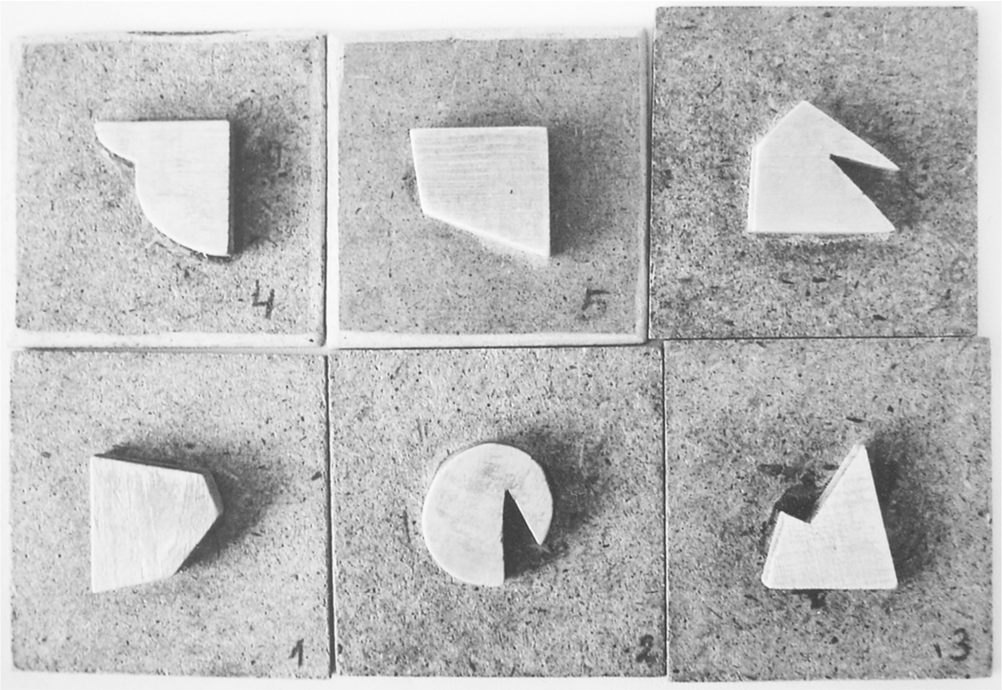
letters (a)

82x55mm (300 x 300 DPI)



geometric shapes (b)

78x53mm (300 x 300 DPI)

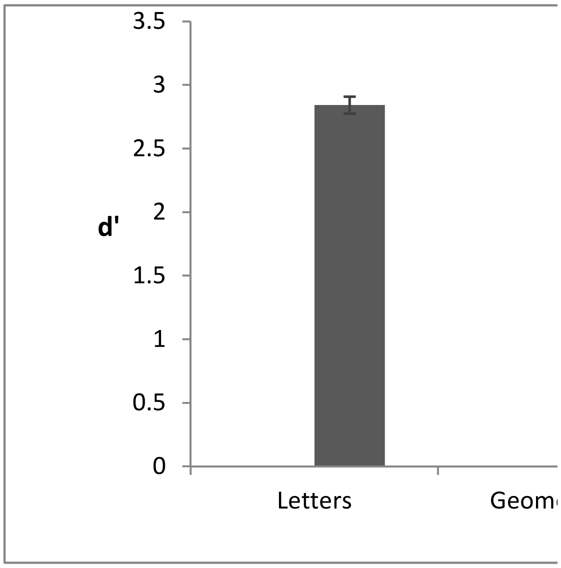


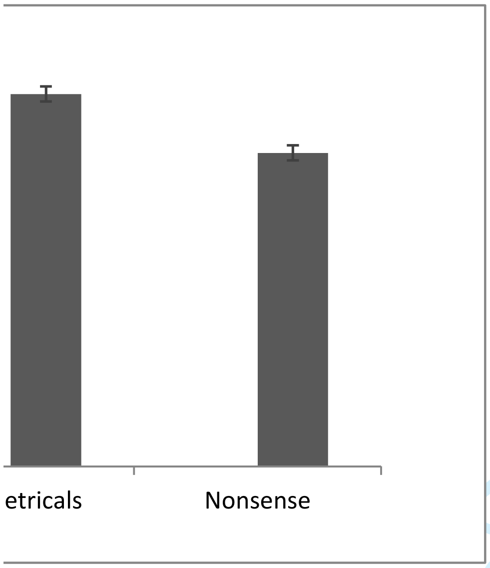
nonsense shapes (c)

82x56mm (300 x 300 DPI)

Stimuli

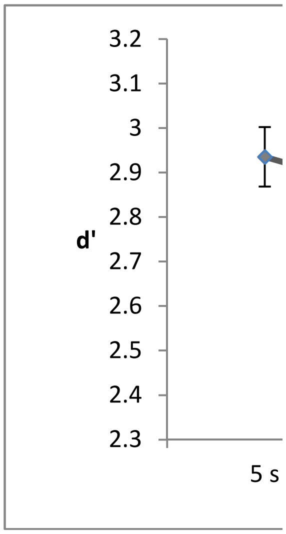
d'	M	SD	SEM
Letters	2.8	0.8	0.1
Geometrica	2.9	0.7	0.1
Nonsense	2.5	0.7	0.1

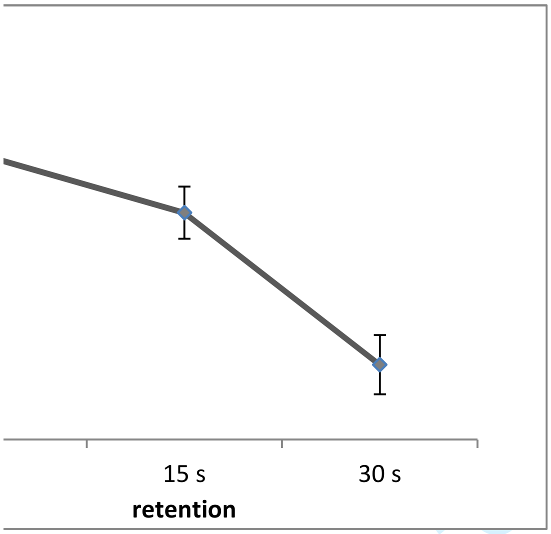



etricals
Nonsense

retention

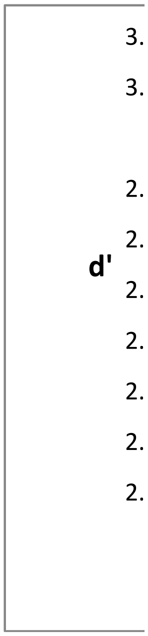
d'	M	SD	SEM
5 s	2.9	0.8	0.1
15 s	2.8	0.7	0.1
30 s	2.5	0.8	0.1

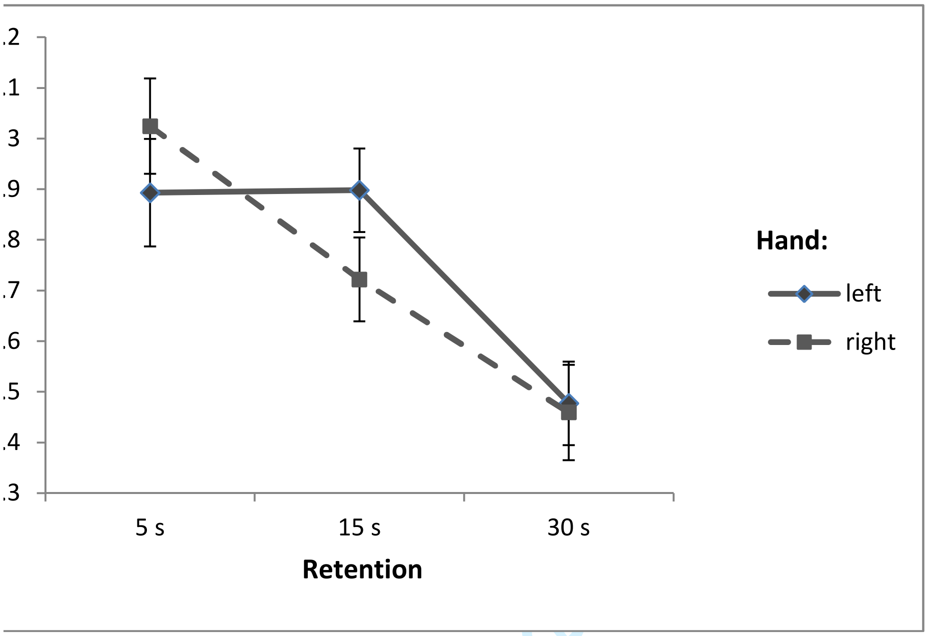



15 s
30 s
retention

Retention * Hand

d'	left			right		
	Mean	SD	SEM	Mean	SD	SEM
5 s	2.9	0.9	0.11	3.0	0.8	0.09
15 s	2.9	0.7	0.08	2.7	0.7	0.08
30 s	2.5	0.7	0.08	2.5	0.8	0.09




.2
.1
3
.9
.8
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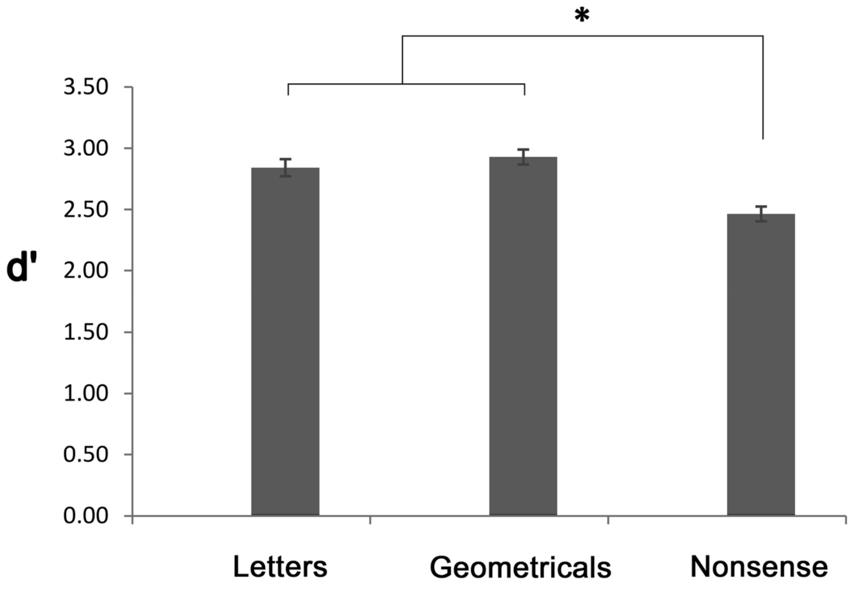
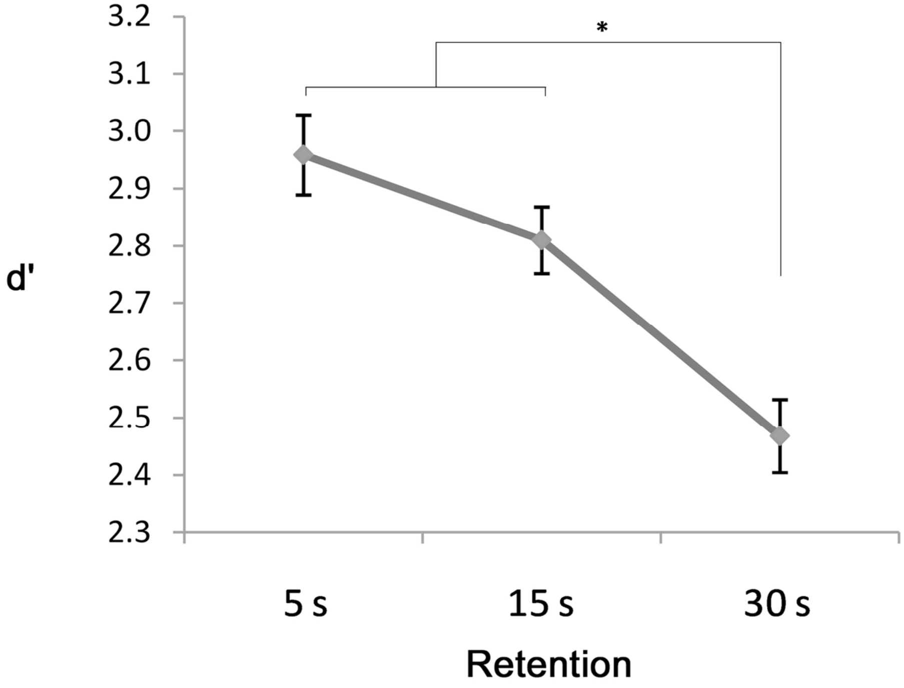
.5
.4
.3
5 s
15 s
30 s
Retention
Hand:
left
right



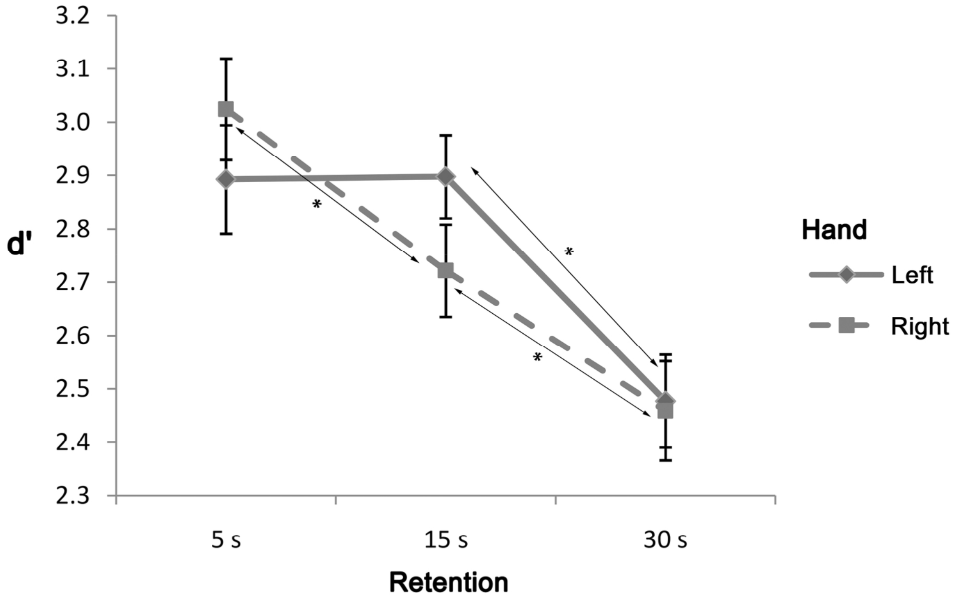
Caption : Performance (d') in unilateral haptic memory discrimination task for three types of stimuli: Haptic discrimination for letters, geometrical shapes and nonsense shapes across retention and hands. The star indicates statistically significant ($p<0.05$) differences. Error bars denote the standard error of the mean

76x54mm (600 x 600 DPI)



a) Unilateral haptic discrimination at 5, 15 and 30 s retention times across stimulus types and hands.

66x53mm (600 x 600 DPI)



b) Unilateral haptic discrimination for each hand as a function of retention time. The stars point out statistically significant ($p<0.05$) differences. Error bars denote the standard error of the mean.

88x58mm (600 x 600 DPI)