

Observation of own exploration movements impairs haptic spatial perception

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Received: 26 March 2013 / Accepted: 7 September 2013
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Abstract The present study was designed to assess whether the visibility of ones' own exploratory movements impairs or enhances perceptual speed and precision of haptic stimuli with varying complexity. Previous studies have shown that noninformative vision of steady surroundings improves haptic spatial perception. However, due to the serial nature of haptic processing and limited capacity of working memory resources, we hypothesized that noninformative vision of limb movements may impair haptic perception. The study sample consisted of ninety-eight healthy adults who were randomized into two groups, matched for sex and age. Participants were required to explore two-dimensional haptic stimuli with varying complexity and to recognize them visually. The difference between the two experimental groups was a screen that would prevent the participants from viewing their hands during exploration in the nonobservation condition (NonOb). The other half of participants were able to see their hands in the manual movement observation condition (MovOb) thanks to the special design of the stimuli. As hypothesized, the persons in the MovOb condition made significantly more errors. The difference in error frequency between participants of the MovOb and NonOb condition was greater for complex stimuli than for simple ones. These results suggest that incoming visual information about own manual exploration movements increases competitive pressure for limited working memory resources, and therefore, more recognition errors are made. Covering the hands during exploration may constitute a helpful simplification of the task's

demands by supporting the maintenance of information in working memory. Additionally, the relation of haptic complexity and stimulus characteristics was analyzed.

Keywords Noninformative vision · Working memory resources · Limited capacity · Sensory integration · Tactile touch · Stimulus complexity

Introduction

Sensory integration and the varying degree of relevant information used from different modalities during perceptual processes have been of increasing relevance in research in the past decade (Igarashi et al. 2010). The rapid development of technical equipment (e.g., in the fields of robotics and laparoscopic surgeries) calls for better understanding of human sensory processing and integration especially of vision and haptics. In recent years, a relevant number of researchers have explored the ramifications of the optimal integration supposition introduced by Ernst and Banks (2002). According to their maximum likelihood rule (MLE rule), visual and haptic information are combined by the organism in a statistically optimal way to achieve a final estimate of the perceived object with a minimally low variance. Depending on the clarity ('variance') of the haptic and visual input, either one of the senses gets a stronger weighting and, therefore, a stronger influence on the perceptual outcome (Hillis et al. 2002). These sensory phenomena have been called visual capture (Tastevin 1937) and haptic capture (Hershberger and Misceo 1996).

Correspondingly, the tactile detection threshold measured by means of two-point discrimination improves under exclusion of visual input (blindfolded subjects versus subjects with hands covered) (Rosen and Bjorkman 2010).

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On the other hand, Taylor-Clarke et al. (2004) showed that when the participants were able to see the stimulated body part, their tactile acuity improved. In their experiment, the visual field contained no information about the stimulus and was therefore considered noninformative. Elsewhere, it has been argued that the somatosensory response to a tactile stimulus is augmented by noninformative vision of the relevant body part and through that tactile perception improves (Harris et al. 2007).

Concerning haptic perception (active exploration as opposed to passive contact without movement during tactile detection tasks), Newport et al. (2002) found that noninformative vision improves haptic spatial perception in peripersonal space. In their experiment, the participants were required to judge whether two bars felt parallel to one another while their eyes were either open and their hands and stimuli covered or they were blindfolded. In line with the MLE model, the authors suggested that noninformative vision influences the relative weighting given to the cues from both modalities favoring the haptic information (Newport et al. 2002).

To the best of our knowledge, the influence of viewing own exploration movements during recognition of haptic properties has not been analyzed yet. In the present study, we will investigate, with the help of specially designed stimuli, the influence of visual information of manual exploration movements on haptic recognition results.

According to MLE rule, haptic capture should occur when the participants are able to see their hands during exploration of obscured stimuli, since the visual information from the exploration movements would be very noisy and unsystematic. Only when participants perform contour following exploration (Klatzky et al. 1987) but not during scanning motions, would their movements contain any additional congruent information about the stimulus structure. Our observations during previous unsystematic experiments have shown, however, that many participants prefer to fix their view to a distant point in the room or even close their eyes during exploration instead of continuously watching their manual exploration movements. This may possibly be done to prevent irrelevant information from flooding limited working memory resources. Therefore, we expect that participants who can see their hands to show inferior recognition results compared to those who are granted only noninformative vision (Hypothesis 1). We will additionally investigate the effect of stimulus complexity on the precision of recognition of haptic stimuli by participants who can see their hands during exploration and those who cannot. Previous studies have assumed that the recognition of haptic stimuli is a serial process that requires working memory resources (Knecht et al. 1996; Wallraven et al. 2013). Previous studies have also shown that informational load (complexity) is negatively correlated with visual working

memory capacity (Eng et al. 2005). According to system theory as well as information theory it is logical to assume that the more information is inherent in a stimulus the more resources will be required to process it. This has been experimentally shown for visual as well as haptic stimuli in various studies (e.g., Ballesteros and Reales 2004). For the present study, two types of stimuli were designed: simple and complex ones. Simple forms were defined as having between one and three elements. Complex forms were to have more than three elements and should be discontinuous and/or disconnected. In the present study, complexity may also be defined as the amount of features that have to be kept in mind during scanning of the visual display after haptic exploration. Semantic stimuli (like a triangle or dots of a die) may require less working memory resources than random forms and may, therefore, lead to fewer recognition errors. To evaluate the relationship between recognition accuracy and stimulus complexity further, we will present detailed stimulus analyses. In line with previous studies, we assume that exploration time will be greater for more complex stimuli in both experimental conditions (Gaschk et al. 1968; Locher and Simmons 1978; Rosler et al. 1993; Grunwald et al. 1999, 2001) (Hypothesis 2).

If as hypothesized above, seeing the hands during exploration coincides with inferior recognition results, we will follow-up on the limited resources hypothesis by further analyzing the influence of stimulus complexity on the number of errors. If viewing the hands during exploration of invisible haptic properties puts an additional strain on working memory resources, this effect should be greater for stimuli with higher complexity (Hypothesis 3).

The present study was designed to assess whether the observation of ones' own exploratory movements impairs or enhances perceptual speed and precision of haptic stimuli with varying complexity.

Methods

Participants

Ninety-eight healthy volunteers (46 males, 52 females; aged between 20 and 55 years; 92 right-handed, 5 left-handed, 1 ambiguous) participated in the present study. They were randomly assigned to one of two experimental conditions, but matched for sex and age (Table 1). The participants consisted of students and staff of the local university of various fields. All participants presented with normal or corrected-to-normal eyesight, took part voluntarily and gave informed consent. They were naive to the stimuli and had never taken part in haptic experiments or similar studies before. All participants that presented with a somatic, neurological, or psychiatric disorder were excluded from

Table 1 Descriptive information of both experimental groups

	MovOb ^a	NonOb ^b	Statistics	
			<i>z</i> ^c	<i>p</i>
<i>n</i>	49	49		
Sex (male/female)	23/26	23/26	0.0	1.0
Age	26.57 ± 8.03 (20–55)	26.71 ± 7.91 (20–54)	–0.21	0.83

^a Manual movement observation condition

^b Nonobservation condition

^c Mann–Whitney *U* test

the study. The study was approved by the local ethics committee of the University Hospital of Leipzig.

Measures and procedure

After the participants were assigned to an experimental condition, they were seated at a table across from the experimenter in a quiet room. The difference between the two experimental settings was a screen that would prevent the participants from viewing their hands during exploration in the nonobservation condition (NonOb). The other half of the participants were able to see their hands in the manual movement observation condition (MovOb). This was made possible by a special design of the stimuli themselves. The

stimuli consisted of two-dimensional raised-line (relief) patterns that were covered by an opaque plastic film (specially manufactured for this purpose to prevent afterimages and imprints) that obscured vision, but allowed free haptic exploration in a comfortable position (Fig. 1a). The opaque plastic film allowed the participants' eyes to remain open at all times in both experimental conditions. Each stimulus had to be explored manually and indicated on a visual display (Fig. 1b; for a more detailed description of the stimuli and setup, see (Grunwald 2010)). The stimuli were designed to differ in complexity. Eighteen simple raised-line forms and 18 complex forms were constructed according to a definition of varying number of elements. (Simple stimuli are marked with a gray capital 'S' in Fig. 1b. These 'S' did not occur on the visual display that was presented to the participants.) Simple forms had between one and three elements, while complex forms had more than three elements which were discontinuous and/or disconnected. The only exception to the rule is stimulus no. 16, which will be considered a simple stimulus due to its strong semantic weight even though it has 4 elements. Size and shape of the haptic stimuli corresponded with the depicted figures on the display that was presented on the table (MovOb condition) or alternatively on the screen that covered the hands (NonOb condition) in front of the participant (Fig. 2). The visual display depicted all possible 36 stimuli at all times. The images were numbered from 1 to 36 (Fig. 1b). When the participant recognized the stimulus, he had to call the

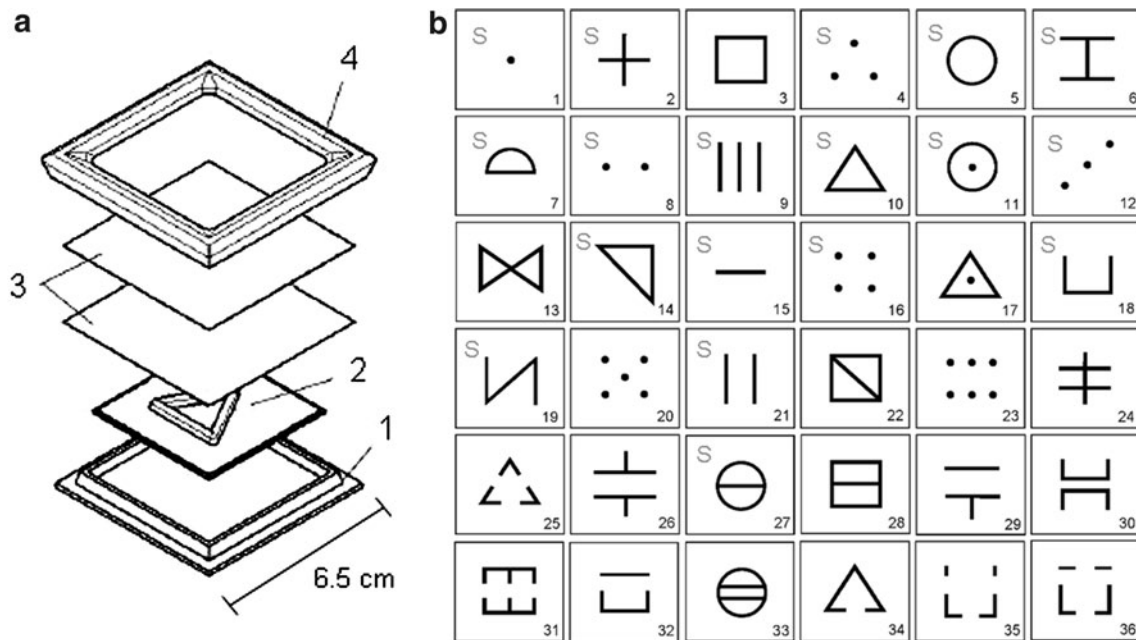
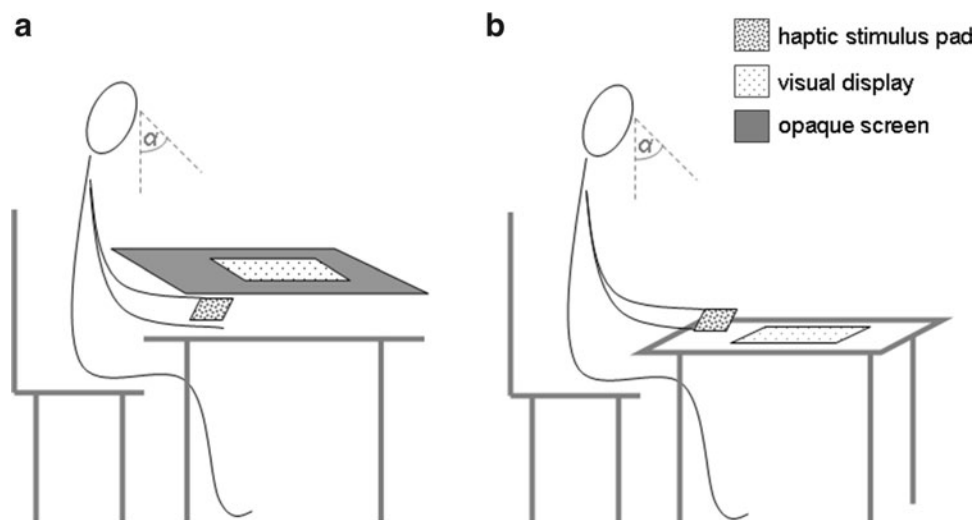


Fig. 1 **a** Construction of the stimuli. 1 base plate; 2 two-dimensional geometric form; 3 opaque plastic film consisting of two layers; 4 bracket/frame. **b** Representation of the visual display of all 36 stimuli numbered from 1 through 36. Original size of the display was 41.5

cm × 38.5 cm with each figure measuring 6.5 cm × 6.5 cm. The display was the same for both groups and visible at all times during the experiment

Fig. 2 Schematic illustration of the two experimental settings. **a** NonOb condition: *opaque screen* covering the hands from sight with the *visual display* on top of the screen. **b** MovOb condition: *visual display* on the table in front of the test subject. Alpha stands for the gaze displacement angle, which was the same for both experimental groups



number of its likeness on the visual display. Exploration time was measured from the first touch of the stimulus until the participant called the number. During the exploration, the participants' forearms rested on the edge of the table. They were free to use any exploration strategy they liked. Typically, the participants switched between holding the stimulus with both hands while exploring with their thumbs and holding the stimulus down on the table with one hand while exploring with the index and middle finger of their other hand. Both experimental conditions (MovOb, NonOb) allowed the participants to direct or even fix their gaze anywhere in the room they liked. However, in both conditions, the requirement of the test to call the number of the stimulus forced the participants to eventually direct their gaze to the visual display to find the answer. The major difference between the NonOb and MovOb condition was that during the MovOb condition, viewing the display would bring the hands and exploration movements within sight. During the NonOb condition, however, viewing the visual display would *not* bring the hands and exploration movements within sight because the hands and stimulus in that condition were below the screen (see Fig. 2). The angle of gaze displacement to look at the visual display was the same in both conditions. The two conditions differed only insofar as the display was about 15 cm closer to the face in the NonOb condition. This had no influence on the visibility of the display.

The experimenter explained the experimental procedure and introduced the participants to a training stimulus. After the participants had understood the setup and gave their consent, the experiment began. The participants were handed 36 stimuli consecutively. Each stimulus was handed to the participant in the same orientation as depicted on the display to prevent varying difficulty and exploration times due to demands of mental rotation. Each stimulus was marked with a little dot on one

side to help the experimenter chose the right orientation. They were presented in random order, but in the same order for every participant. There was no time limit set for the exploration. The participants were told to take their time and that accuracy was more important than speed.

Additionally to exploration time, recognition errors were assessed during the experiment.

Statistical analyses

Data were aggregated for correct stimuli (t_{corr}) and wrong stimuli (t_{wrong}) as well as simple and complex stimuli to calculate mean exploration times and number of errors for each participant. Mann–Whitney U tests were used to compare MovOb and NonOb groups to account for heterogeneous variances.

As a preparation to the stimuli analyses, exploration times and errors were aggregated for each stimulus (Table 2). Mann–Whitney U tests were used to compare exploration times of simple and complex stimuli. Standard Pearson correlation was used to analyze the relationship between the number of errors and exploration time. Additionally, explorative Mann–Whitney U tests were conducted to compare stimuli with round and angular forms as well as stimuli with dots and lines.

To test if the difference in number of errors between the two groups differed for the two complexity levels, Mann–Whitney U tests were performed, to account for the non-central F-distribution of the data.

Results

The two samples (MovOb and NonOb group) were equal with respect to sex and age (Table 1).

Table 2 Number of errors and mean exploration time per stimulus

Stimulus no. ^a	Sum of errors per stimulus		Mean exploration time ^b	
	MovOb	NonOb	<i>M</i>	(SD)
1	0	0	10.18	(4.53)
2	3	3	29.50	(22.41)
3	20	12	43.60	(31.05)
4	0	0	14.03	(10.92)
5	1	0	13.55	(12.12)
6	2	3	26.94	(17.68)
7	3	1	17.95	(12.21)
8	0	0	9.08	(3.93)
9	2	3	20.82	(13.65)
10	1	0	21.10	(14.89)
11	1	1	17.22	(12.77)
12	0	0	11.44	(4.40)
13	5	2	50.84	(43.84)
14	2	0	24.82	(17.19)
15	0	0	12.69	(7.71)
16	0	0	9.69	(5.97)
17	4	2	20.30	(13.13)
18	0	0	21.12	(12.64)
19	0	0	23.68	(16.55)
20	2	0	9.62	(7.11)
21	2	0	22.11	(15.10)
22	4	4	27.02	(20.45)
23	8	13	25.39	(23.28)
24	16	10	31.36	(19.10)
25	2	0	29.29	(21.56)
26	11	7	18.89	(12.71)
27	15	2	24.64	(16.35)
28	8	1	31.42	(27.71)
29	0	0	31.08	(26.84)
30	2	3	29.73	(22.18)
31	8	3	40.68	(24.22)
32	4	1	26.00	(18.32)
33	3	1	22.20	(22.54)
34	1	0	18.09	(10.98)
35	2	2	32.01	(28.16)
36	3	4	31.80	(21.75)
Total errors	135	78		

^a Errors were made primarily with stimuli 3, 13, 23, 24, 26, 27, 28, and 31

^b Mean exploration time across all test subjects, *N* = 98

Men and women performed equally well (MovOb: $z_{\text{errors}} = -1.56$; $p = 0.12$; $z_{t_{\text{corr}}} = -0.30$; $p = 0.48$; $z_{t_{\text{wrong}}} = -0.18$; $p = 0.86$; NonOb: $z_{\text{errors}} = -0.19$; $p = 0.85$; $z_{t_{\text{corr}}} = -0.13$; $p = 0.89$; $z_{t_{\text{wrong}}} = -0.07$; $p = 0.94$).

Age was slightly correlated with exploration time, but not with the number of errors ($r_{t,\text{age}} = 0.262$, $p < 0.05$; $r_{\text{errors},\text{age}} = 0.103$; $p = 0.31$).

Hypothesis 1: Visibility of movement versus noninformative vision

Analyses showed a significant difference of the two experimental groups in their total number of errors (Table 3), but not in their exploration time for wrong stimuli or their exploration time of stimuli recognized correctly. The participants in the MovOb condition made significantly more errors (Table 2) while the exploration times were the same in both groups. This group difference was not due to just a few people. After exclusion of three possible outliers with 8, 9, and 11 errors, the difference between the two groups remained significant ($z = -2.276$, $p < 0.05$). The top three stimuli with the most errors were stimuli 3, 24, and 27. A total of 40.8 % of the participants in the MovOb condition made a recognition error with stimulus number 3, while only 26.5 % of participants in the NonOb condition did. Stimulus 24 was mistaken by 32.7 % of the participants in the MovOb condition and 20.4 % of the participants in the NonOb condition. The difference for stimulus number 27 was even more impressive because 30.6 % of the participants of the MovOb group made an error, but only 4.1 % of the NonOb group did.

Hypothesis 2: Stimulus complexity

A significant medium correlation was found for number of errors and mean exploration time per stimulus ($r_{\text{errors},\text{time}} = 0.465$, $p < 0.001$). As expected, comparisons between the two complexity groups revealed significant differences in exploration time ($z = -4.557$, $p < 0.001$; $M_{\text{simple}} = 18.01$, $SD = 6.7$; $M_{\text{complex}} = 28.63$, $SD = 10.3$). Additionally, significant differences in number of errors were found ($z = -4.793$, $p < 0.001$; $M_{\text{simple}} = 0.82$, $SD = 1.14$; $M_{\text{complex}} = 4.97$, $SD = 5.21$).

In both experimental groups, errors were made primarily with stimuli numbers 3, 13, 23, 24, 26, 27, 28, and 31 (Table 2). There were five stimuli that were more prone to errors than the other stimuli ($z = -4.755$, $p < 0.001$; $M_{\text{errors}} = 11.7$, $SD = 5.33$; $M_{\text{rest}} = 1.61$, $SD = 1.91$; stimuli 3, 23, 24, 26, 27; see Table 2). When compared to all other stimuli, they did not differ in mean exploration time, however ($z = -1.726$, $p = 0.084$; $M_{\text{errors}} = 28.78$, $SD = 9.68$; $M_{\text{rest}} = 22.78$, $SD = 10.15$). Out of all stimuli, the dotted ones with up to five dots (stimuli 1, 4, 5, 8, and 12), the horizontal line (stimulus 15), and the circle (stimulus 16) were recognized the fastest and with almost no errors.

Table 3 Differences in exploration time and number of errors between MovOb and NonOb

	MovOb ^a (<i>n</i> = 42)		NonOb ^b (<i>n</i> = 42)		Statistics	
	<i>M</i>	(SD)	<i>M</i>	(SD)	<i>z</i> ^c	<i>p</i>
Errors	2.86	(2.46)	1.61	(1.51)	-2.699	0.007
t_corr ^c	22.23	(9.63)	23.29	(5.46)	-1.808	0.071
t_wrong ^d	37.36	(29.52)	33.45	(19.05)	-0.261	0.794

^a Manual movement observation condition

^b Nonobservation condition

^c Exploration time of correct stimuli

^d Exploration time of wrong stimuli

^e Mann–Whitney *U* test

Fig. 3 Round stimuli were numbers 5, 7, 11, 27, and 33. Matching angular forms were stimulus numbers 3, 10, 18, 22, and 28. Dotted stimuli numbers 1, 4, 8, 12, 16, and 20 were compared to stimuli with matching numbers of lines (stimuli 9, 15, 18, 19, and 21)

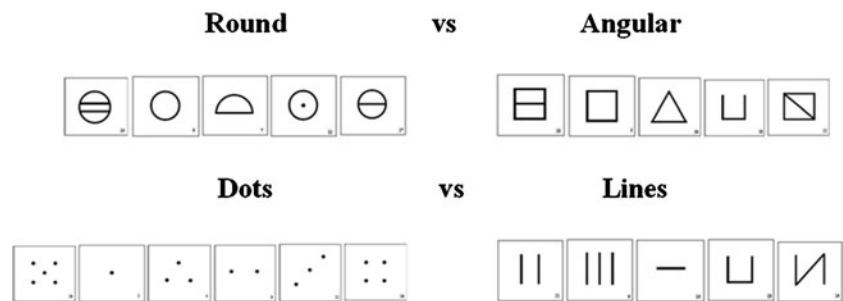


Table 4 Explorative stimulus shape analyses

Stimulus shape	Exploration time <i>M</i> (SD)	Statistics		Number of errors <i>M</i> (SD)	Statistics	
		<i>z</i> ^c	<i>p</i>		<i>z</i> ^c	<i>p</i>
Dots versus lines ^a	10.68 (2.10)	-3.561	<0.001	0.17 (0.58)	-1.326	0.185
	20.07 (4.29)			0.70 (1.16)		
Round versus angular ^b	19.23 (4.94)	-2.57	<0.05	2.90 (4.70)	-0.349	0.727
	28.77 (9.35)			5.20 (6.91)		

^a Dotted stimuli 1, 4, 8, 12, 16, and 20 were compared to stimuli with matching numbers of lines (stimuli 9, 15, 18, 19, and 21)

^b As round stimuli numbers 5, 7, 11, 27, and 33 were used. Matching angular forms were stimulus numbers 3, 10, 18, 22, and 28

^c Mann–Whitney *U* test

Additionally, effects of shape were analyzed further by comparing paired stimuli of the following types: round versus angular, dots versus lines (see Fig. 3). Paired comparisons indicated that round stimuli were recognized faster than angular stimuli ($p < 0.05$), and dots were recognized faster than lines ($p < 0.001$). The differences in number of errors per stimulus were not significant for either of the paired groups (Table 4).

Hypothesis 3: Difference in recognition errors for simple and complex stimuli

The difference in number of errors between participants of the MovOb and NonOb condition was greater for complex stimuli ($M_{\text{MovOb}} = 2.41$, $SD = 2.13$, $v = 1.00$;

$M_{\text{NonOb}} = 1.35$, $SD = 1.47$, $v = 1.21$; $z = -2.631$, $p < 0.01$) than for simple ones ($M_{\text{MovOb}} = 0.35$, $SD = 0.75$, $v = 2.39$; $M_{\text{NonOb}} = 0.22$, $SD = 0.47$, $v = 1.98$; $z = -0.398$, $p = 0.691$), with more errors in the MovOb group (Fig. 4). However, it should be noted that the error rates for simple stimuli were close to zero; therefore, the differences in the two conditions may have been harder to detect.

Discussion

The present study was designed to examine how the visibility of own manual movements during a haptic exploration task influences the recognition process. We hypothesized that those participants who could see their hands (MovOb)

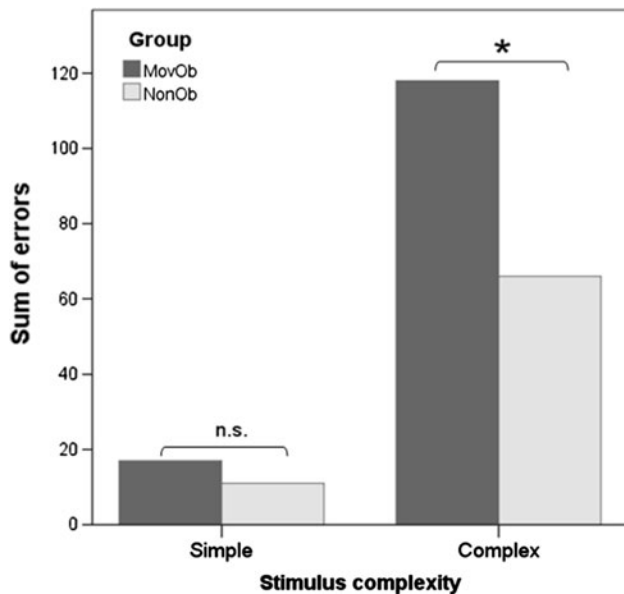


Fig. 4 Bar chart depicting the sum of errors of both experimental groups for both simple and complex stimulus sets. The *asterisk* indicates a significant difference between the groups for complex stimuli. The difference between the experimental groups for simple stimuli was not significant

would show inferior recognition results compared to those (NonOb) who were only granted noninformative vision (Hypothesis 1). The hypothesis was confirmed. Accordingly, participants who were granted noninformative vision with their hands out of sight (NonOb) made less recognition errors than participants with noninformative vision who could see their hands (MovOb). This difference was not due to outliers. The participants in the MovOb group made almost twice as many mistakes as those in the NonOb group, which is immense considering that all stimuli consisted of relatively simple figures.

For both groups, a medium correlation between mean exploration time and number of errors was found. As exploration time has been shown to be associated with informational load of visual as well as haptic stimuli (Ballesteros and Reales 2004), this finding may indicate an increase in errors with increasing stimulus complexity. However, there were five stimuli that were more prone to errors than most other stimuli (stimuli 3, 23, 24, 26, 27), but three of them only reached medium mean exploration times. Assessing complexity is a difficult task as no strict theoretical foundations have been set yet for haptic properties. The primarily considered aspect for an increase in complexity is an increase in features or details (increase in informational load; increase in turns), which may coincide with an increased exploration time (Gaschk et al. 1968; Locher and Simmons 1978; Brennan et al. 1984; Ballesteros and Reales 2004). According to logic, more errors should have

occurred with more difficult stimuli. However, as has been shown before, complexity (informational load) and difficulty (subjective complexity) are not necessarily the same thing (Attneave 1957).

For simple stimuli, the number of errors and exploration time were significantly lower than for complex stimuli. With the more complex stimuli, however, variability in the number of errors of the participants increased as might have been expected. Individuals differ in their haptic sensitivity from birth (Montague 1978), which may account for the inter-individual variability in the number of errors at least partially. Besides inter-individual differences in sensitivity differences in concentration, attention, spatial perception, and thoroughness may play a role and may possibly act as moderating variables of the correlation between complexity and errors. In future studies, stimuli with greater differences in complexity should be used (especially more stimuli with higher complexity) to find greater differences in the number of errors between the groups.

Concerning haptics little is known, if for example multiple dots are easier to decipher than multiple lines or the other way around or if curves are more difficult to decipher than edges in raised-line forms. In our set of stimuli, the ones with dots were recognized the fastest and most accurate out of all stimuli. However, this may have been mediated by semantics, because the dots were arranged like on dice. Kreitler (1974) have argued that visual stimuli with several elements that may be perceived as an overall structure may be rated simpler than nonsense stimuli with fewer elements. This same mechanism may be relevant for haptic stimuli. Six dots arranged like on a die, however, were extremely often mistaken for apparently more complex stimuli. Why this was the case cannot be answered within the scope of this study. Possibly, haptic illusions played a role and ambiguity errors between similar stimuli (e.g., stimuli 24, 26, 29 and stimuli 3, 18, 32). Additionally, paired comparisons indicated that round stimuli were recognized faster than angular stimuli, but not more accurately. However, according to their number of turns, the informational load of curves should be higher than that of angles (Attneave 1957). A similar effect has been shown before for visual stimuli when curved shapes were rated with the same subjective complexity as angular shapes (Attneave 1957).

Haptic capture or any other weighing of the sensory input favoring haptic information could not be observed. It may very well be that haptic capture may have been observed for the NonOb group when compared to a blindfolded sample. However, due to the special design of the experimental conditions, blindfolding the participants would have altered the task to a degree that would have made comparisons between groups impossible. One possible explanation why we did not observe haptic capture

in the MovOb group may be that the visual information inherent in the exploration movements was not categorized as noisy. Under which circumstances sensory input is considered noisy or dominant and is merged with information from other sensory modalities has not been evaluated conclusively (Ernst and Bulthoff 2004). In our study, visibility of own exploration movements seems to constitute an interfering factor to solving the present task.

Haptic information has been shown to be processed in a serial manner (Knecht et al. 1996). We hypothesized that the visibility of own exploration movements may disturb the serial process of haptic perception. Although visibility of the hands facilitates accurate focussing of spatial attention in the direction of the stimulus, the observation of own movements proves a great demand to cognitive filters and subsequently to sustaining spatial working memory (Lawrence et al. 2001). In daily life, implicit awareness that visual motion information does not contain any reliable additional information to a haptic perception task (e.g., feeling a smooth surface or searching something in a bag) will lead to active exclusion of visual input either by closing the eyes or fixating a distant point. In our experiment, participants were required to compare their haptic percept to a visual display of the stimuli. That is, an internal representation of the stimulus had to be formed via serial cognitive processing, which in turn had to be matched via visual scanning to one of the stimuli on the visual display. This problem alone poses a challenge to working memory maintenance. Voluntary eye movements (e.g., visual scanning) have been shown to disrupt spatial working memory contents (Postle et al. 2006). Similar disruptive effects have also been found for limb movements (Lawrence et al. 2001).

Therefore, it is likely that incoming visual information during visual scanning of the display competes with the maintenance of the internal representation of the haptic stimulus for limited working memory resources of the spatial scratch pad. Visibility of the hands and incoming visual information of the exploration movements may have put additional strain on working memory resources and cognitive filters. We hypothesized that if the higher number of errors in the MovOb group really was due to limited capacity of working memory resources, we should find a significant difference in number of errors of the two groups only for complex stimuli with more errors in the MovOb group (Hypothesis 3). The results show that more information inherent to the stimulus resulted in more difficulty to recognize it (more errors with complex stimuli than simple ones) in both groups, with more errors in the MovOb group for both simple and complex stimuli. But the difference in number of errors was significant only for complex stimuli. As the two experimental groups were the same in both experimental setup and subject characteristics, but differed only insofar as the hand movements were within the visual

field for the MovOb group, while they were covered from sight for the NonOb group, we conclude that incoming visual information of own manual exploration movements increased competitive pressure of various sensory information for limited working memory capacity, and therefore, more recognition errors were made. Movement as opposed to visual input of stationary surroundings may capture attention due to orienting responses (OR) and may, therefore, be more salient than the incoming haptic information (Diao and Sundar 2004). In the context of the limited capacity model that means that the attention shifts evoked by the OR would result in a further decrease in already small available resources for other simultaneous processes such as maintaining and retrieving haptic stimulus information (Lang 2000). The shifts in attention may interfere with the visual–haptic comparison task because they disrupt internal rehearsal processes of the internal representation of the stimulus (Smyth and Scholey 1994; Awh et al. 1998).

To further evaluate these possibilities, future studies should conduct eye-tracking measures and manual movement analyses. To verify the influence of orienting responses, the typical physiological changes that coincide with OR (e.g., pupil dilation and decreased alpha waves in the brain) should be measured (Lynn 1966). Additionally, future studies may evaluate the possible relevance of distraction due to movement in general within the visual field as well as inter-individual differences between distractibility and attention.

In summary, we found that own manual movement observation exacerbates haptic perception. This may be a general effect of visible movements during the difficult haptic tasks. Covering the hands may, therefore, constitute a helpful simplification of the task's demands by supporting the maintenance of information in working memory. This finding may have relevant implications for computer-assisted surgery and other human–machine interaction settings.

Acknowledgments This research project was supported in part by the Deutsche Forschungsinitiative Eßstörungen (DFE e.V.) and the Haptik-Forschungszentrum. Neither had influence on the preparation of the article nor the conduct of the research.

Conflict of interest None.

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