Long-Term Memory for Haptically Explored Objects: Fidelity, Durability, Incidental Encoding, and Cross-Modal Transfer

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This manuscript was accepted for publication in *Psychological Science*.

This is a preprint. Please refer to the publisher's website for the version of record.

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Abstract

The question of how many of our perceptual experiences are stored in long-term memory has received considerable attention. The present study examined long-term memory for haptic experiences. Blindfolded participants haptically explored 168 everyday objects (e.g., a pen) for ten seconds each. In a blindfolded memory test, they indicated which of two objects from the same basic-level category (e.g., two different pens) had been touched before. As shown in Experiment 1 (N = 26), memory was nearly perfect when tested immediately after exploration (94%) and still high when tested after one week (85%). As shown in Experiment 2 (N = 43), when participants explored the objects without the intention to memorize them, memory in a one-week delayed surprise test was still high (79%), even when assessed with a cross-modal visual memory test (73%). These results indicate that detailed, durable long-term memory representations are stored as a natural product of haptic perception.

Keywords: haptic memory, perceptual memory, cross-modal memory, object memory, memory capacity

Long-Term Memory for Haptically Explored Objects: Fidelity, Durability, Incidental Encoding, and Cross-Modal Transfer

Imagine you are strolling around in a shopping mall on a lazy day, detecting a large rummage table with hundreds of different objects. Just for fun, you explore the objects, often even not looking at the objects your hands are touching. One week later, someone surprisingly asks you about your memories for the objects you have touched without looking at them. Would you remember the haptic experiences you have made while touching the objects? If so, how detailed would your haptic memories be? And if your haptic memories were detailed, would you even be able to visually recognize these objects although you have never seen them before? The aim of the present study was to examine these questions.

The question of how many of the thousands of perceptual experiences we make during a day are stored in long-term memory has received considerable attention. At first glance, one may assume that it is unlikely that the majority of perceptual experiences are stored in long-term memory. First, an overwhelming amount of information would have to be stored, and second, this seems not functional, especially if there is no intention to remember the perceptual experience. However, intriguing findings in the domain of visual long-term memory indicate that humans indeed store an extraordinary large number of perceptual experiences. First evidence comes from landmark studies in the 1970s, demonstrating that after viewing 10,000 real-world photographs for only 5 sec each across five consecutive days, observers could determine which of two photographs had been presented with a remarkably high accuracy of 83% (Standing, 1973). Even more surprising, more recent studies have shown that the stored long-term memory representations consist not only of the “gist” of the photographs. Rather, observers could successfully determine which of two photographs had been presented with high accuracy even when the photographs differed only in subtle details (Brady, Konkle, Alvarez, & Oliva, 2008; Konkle, Brady, Alvarez, & Oliva, 2010; Vogt & Magnussen, 2007), suggesting that high-fidelity representations are stored. Finally, it has been shown that visual experiences are even stored when there is no intention to memorize them (Castelhano & Henderson, 2005; Kuhbandner, Rosas-Corona, & Spachtholz; 2017; Williams, Henderson, & Zacks, 2005), indicating that long-term memory representations are formed as a natural product of visual perception. In view of these findings, it has been concluded that the storage capacity of human long-term memory is much more massive than commonly believed (Brady et al., 2008).

However, when making an experience in real life, the experience is typically not restricted to the visual modality, but involves other sensory modalities as well. For instance, when exploring an object, several non-visual sensations have to be extracted and integrated, such as texture, hardness, and weight (e.g., Martinovic, Lawson, & Craddock, 2012). Critically, whereas much research has focused on long-term memory for visually explored objects, relatively little is known about long-term memory for experiences in other sensory modalities. With regard to storage capacity, if object experiences in other sensory modalities are stored in similar quantity and quality in long-term memory as experiences in the visual modality, then the capacity of long-term memory would be even larger than estimated based on the abilities of visual long-term memory alone.

The main aim of the present study was to measure the ability to store haptic experiences in long-term memory. Previous research has already shown that objects can generally be identified through haptic exploration alone (Klatzky, Lederman, & Metzger, 1985), and that haptically explored objects can indeed be recognized above chance after a delay of up to one week (e.g., Pensky, Johnson, Haag, & Homa, 2008; for a review, see Gadelha et al., 2013).

However, little is known about the true memory abilities of the haptic long-term memory system. In all of the previous studies on memory for haptically explored objects, memory tests have been used that heavily relied on recollective experience (i.e., single item old/new recognition tests) and may thus not have been sensitive enough to reveal the actual amount of information stored in haptic long-term memory (Cunningham, Yassa, & Egeth, 2015; Guerin, Robbins, Gilmore, & Schacter, 2012).

Beyond measuring the quantity and fidelity of long-term memory representations for haptically explored objects, a second aim of the present study was to examine whether objects that have been perceived in one sensory modality can be recognized in a memory test in another sensory modality (i.e., cross-modal object recognition). Previous research has shown that cross-modal object recognition is indeed possible above chance (e.g., Bushnell & Baxt, 1999), even when memory is tested after a delay of one week (Pensky et al., 2008). However, to our knowledge, all existing studies on cross-modal recognition have used less sensitive memory tests (single item old/new recognition tests). Hence, the true quantity and fidelity of cross-modal object recognition is still unknown.

To measure the quantity of haptic experiences that is stored in long-term memory and the fidelity of these memory representations, in Experiment 1, we adopted the visual-memory paradigm used by Brady and colleagues (2008; for an illustration, see Fig. 1a). Participants were blindfolded and haptically explored 168 different everyday objects for 10 seconds each for a later memory test. To measure memory for the objects, a blindfolded haptic recognition test was used where two objects were given to participants, one previously explored old object, and one new foil object (two-alternative forced-choice test). The two objects belonged to the same basic-level category and differed only in subtle haptic details (for examples, see Fig. 1a). To measure the durability of the stored representations, half of the objects were tested immediately after the study phase, the other half was tested after one week.

In Experiment 2, we made three modifications. First, to rule out the possibility that the results of Experiment 1 were attributable to intentional memorization strategies beyond haptic exploration (e.g., storing haptic information as verbal descriptions), an incidental encoding task was used. Participants were asked to explore the same 168 everyday objects with the aim of making aesthetic judgments, without mentioning that their memory for the objects would be tested later. Memory for the objects was tested in a surprise memory test after one week. If memory performance is still high, then also haptic experiences are stored as a natural product of haptic perception, similar to visual experiences. Second, to examine cross-modal transfer, in the surprise memory test, half of the objects were tested in a blindfolded haptic recognition test (unimodal recognition) whereas the other half were tested in a visual recognition test (cross-modal recognition). Third, to examine whether the participants' memory responses were guided by experiences of recollection (remembering episodic details) or familiarity (feeling of knowing), they were asked to provide metamemory judgments (remember vs. know vs. guess) for each of their responses.

Experiment 1

Method

Participants. Following previous work in the domain of visual long-term memory with sample sizes between 14 (Brady et al., 2008) and 24 (Vogt & Magnussen, 2007), we decided to collect data from at least 24 participants and continue data collection until the end of a semester. In total, we recruited 26 undergraduate students (15 females, M_{Age} = 23.85 years, *SD* = 3.99) who participated for course credit. All provided written informed consent, and all data exclusions, manipulations, and measures in the study are reported.

Materials. The stimulus set consisted of 168 pairs of categorically distinct everyday objects. Each pair of objects consisted of two exemplars that belonged to the same basic-level category and differed only in haptic details. Although the two exemplars had to be haptically distinguishable, effort was made to keep the differences between them as small as possible (for examples, see Figure 1a; for a list of all objects, see Table S1 in the Supplemental Material available online; images of the stimuli can be downloaded at https://osf.io/p3bgz/?view_only=91e864a919df4d8da6a8a5dffe2158bc).

Design and Procedure. After being blindfolded, participants haptically explored one of two exemplars of all 168 object pairs; the assignment of the exemplars of an object pair to the study phase was counterbalanced across participants. Participants were instructed to remember the objects for a later memory test, and to pay attention to object details such as texture, shape, and weight. Each object was presented for 10 seconds, followed by the presentation of the next object. The presentation of all objects took about one hour; presentation order was random. There was a 5-minute break after exploration of half of the objects.

Memory for half of the objects was tested in an immediate test five minutes after the presentation of the last object; the other half was tested in a delayed memory test one week later. The assignment of objects to the immediate and delayed tests was counterbalanced across participants. In both memory tests, after being blindfolded again, participants were presented the previously explored exemplar together with the corresponding exemplar that had not been presented. Participants were instructed to indicate the object that had been explored before. Presentation order was random, and participants proceeded at their own pace.

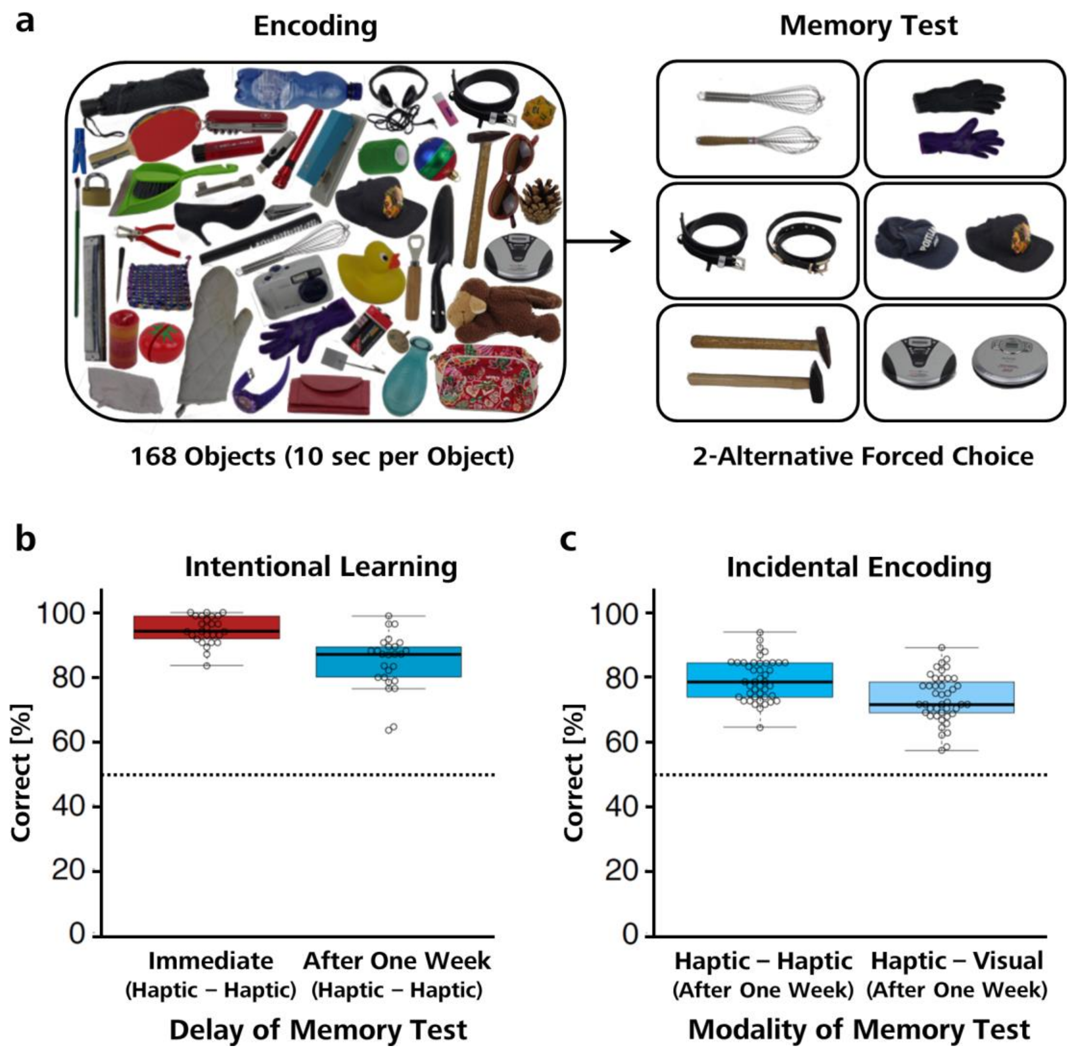

Figure 1. **Memory paradigm and recognition performance**. The procedure of Experiments 1 and 2 is illustrated in (a). In an initial encoding phase, blindfolded participants haptically explored 168 everyday objects for 10 seconds each. Subsequently, memory was tested using a two-alternative forced-choice recognition test with foil objects that belonged to the same basic-level category and differed only in haptic details. In Experiment 1, participants intentionally memorized the objects, and memory for the objects was tested in a blindfolded haptic recognition test either immediately afterwards or after one week. In Experiment 2, participants encoded the objects without the intention to memorize them, and memory for the objects was tested after one week in either a unimodal haptic or a cross-modal visual recognition test. The results of Experiment 1 are depicted in (b). The box plots show participants' memory

performance in the immediate and the delayed tests after one week. The results of Experiment 2 are depicted in (c). The box plots show participants' memory performance after one week in the unimodal haptic and the cross-modal visual recognition test. Center lines show the medians. Box limits indicate the 25th and 75th percentiles. Whiskers extend 1.5 times the interquartile range from the 25th and 75th percentiles. Data points are plotted as open circles. The dashed lines indicate chance performance.

Results

Memory performance in the immediate and 1-week delayed memory tests is shown in Figure 1b. In the immediate memory test, nearly perfect object memory was observed, with participants correctly reporting the previously explored exemplar on 94.4% of the trials (*SD* = 4.3, 95% CI [92.7%, 96.0%]). Even more intriguing, the results for the delayed memory test showed that memory performance was still remarkably high after a delay of one week. Participants correctly reported the previously explored exemplar on 84.6% of the trials (*SD* = 8.6, 95% CI [81.3%, 87.9%]), with relatively little forgetting across the delay of one week ($M_{\text{Difference}}$ = 9.8%, *SD* = 6.9, 95% CI [7.0%, 12.6%]), $t(25) = 7.18$, $p < .001$, $d = 1.44$, 95% CI [0.87, 1.99].

Experiment 2

Method

Participants. In order to replicate and extend the findings of Experiment 1 with a larger sample, 48 undergraduate students participated for course credit. Five of them were excluded from the analysis because they had expected a test according to the post-experimental questionnaire (see below; three expected a memory test, two expected an aesthetic judgment task on the same objects), resulting in a sample of 43 participants (39 females, M_{Age} = 20.26 years, *SD* = 2.23).[1] All participants provided written informed consent, and all data exclusions, manipulations, and measures in the study are reported. Experiment 2 was preregistered (see https://osf.io/p3bgz/?view_only=91e864a919df4d8da6a8a5dffe2158bc).

Material, Design, and Procedure. The stimulus set was the same as in Experiment 1. The procedure was largely similar to Experiment 1 with two exceptions. As in Experiment 1, after being blindfolded, participants haptically explored one of two exemplars of all 168 object pairs for 10 seconds each. However, instead of instructing participants to intentionally memorize the objects for a later memory test, an incidental encoding instruction was used. Participants were told that the aim of the study was to collect aesthetic judgments for everyday objects, and they were asked to rate the pleasantness of each object on a seven-point Likert scale directly after having explored it (1 = "very unpleasant", 7 = "very pleasant"). To assure that the participants explored the objects thoroughly, they were told that aesthetic judgments may depend on small details, and that they should hence pay attention to the objects' texture, shape, and weight. The necessity of a second session after one week was explained by claiming that the stimulus set consisted of too many objects to present all of them during one session. To ensure that encoding was indeed incidental, after completion of the surprise memory test in the second session after one week, participants were asked whether they had expected that their object memory would be tested.

After one week, memory for the objects was tested in a surprise memory test. Half of the initially explored objects were tested using the same blindfolded haptic two-alternative forced-choice recognition test as in Experiment 1 (unimodal recognition test). The other half of the objects were tested in a visual two-alternative forced-choice recognition test (cross-modal recognition test). The visual recognition test was similar to the haptic recognition test with the only difference that the two exemplars of an object pair were put on a table in front of the participants with the instruction to visually indicate which of the two exemplars they had previously explored without touching the objects. The assignment of objects to the visual and haptic recognition tests was counterbalanced across participants. To additionally examine whether the participants' memory responses were guided by experiences of recollection or familiarity, they were asked to provide metamemory judgements. For each response in the recognition tests, participants were asked to indicate whether they *remembered* having touched the chosen object (recollection), whether they had a vague feeling of *knowing* the chosen object (familiarity), or whether they had purely *guessed*.

Results

Memory Performance. Memory performances in the unimodal haptic recognition test and the cross-modal visual recognition test are shown in Figure 1c. Memory performance was remarkably high in both the unimodal haptic and the cross-modal visual test. In the haptic test, participants correctly reported the previously explored exemplar on 79.2% of the trials (SD = 6.4, 95% CI [77.2, 81.2]). In the visual test, participants correctly reported the previously explored exemplar on 73.3% of the trials (SD =7.3, 95% CI [71.1, 75.6]). Performance in the unimodal haptic test was better than in the cross-modal visual test ($M_{\text{Difference}}$ = 5.9%, SD = 6.9, 95% CI [3.8, 8.0]), $t(42) = 5.58$, $p < .001$, $d = 0.86$, 95% CI [0.50, 1.20].

Metamemory Judgments. We first determined the frequency of the three types of metamemory judgments. Figure 2a shows the percentages of memory responses rated as remembered, known, or guessed, depending on the type of recognition test. In the unimodal haptic recognition test, for one third of their responses, participants claimed to have remembered the chosen object (M = 33.6%, SD = 14.2, 95% CI [29.2, 38.0]), for one third they claimed to have a feeling of knowing the chosen object (M = 33.6%, SD = 10.9, 95% CI [30.2, 36.9]), and for one third they claimed to have guessed (*M* = 32.8%, *SD* = 15.6, 95% CI [28.0, 37.6]). In the cross-modal visual recognition test, the frequency of remember judgments decreased (*M* = 25.3%, *SD* = 15.3, 95% CI [20.6, 30.0]), $t(42) = -5.39$, $p < .001$, $d = 0.56$, 95% CI [0.32, 0.80], and the frequency of guess judgments increased (*M* = 41.5%, *SD* = 16.3) , 95% CI [36.5, 46.5]), $t(42) = 6.29$, $p < .001$, $d = 0.54$, 95% CI [0.34, 0.75], with no significant change in the frequency of know judgments (*M* = 33.2%, *SD* = 11.9, 95% CI [29.5, 36.9]), $t(42) = 0.35$, $p = .725$, $d = 0.03$, 95% CI [-0.22, 0.15].

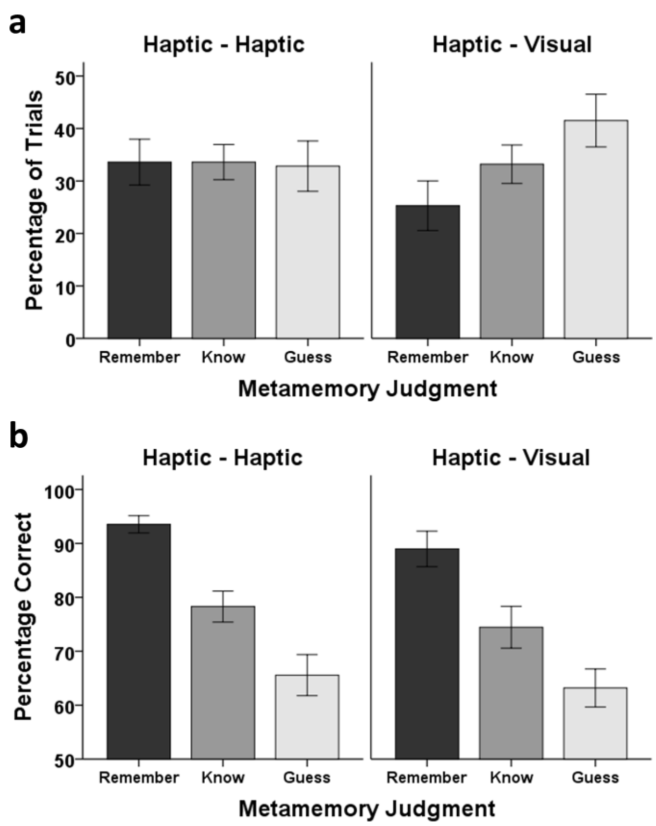

Figure 2. **Metamemory Judgments in Experiment 2**. The percentages of memory responses rated as remembered, known, or guessed in the unimodal haptic (left panel) and the cross-modal visual recognition test (right panel) is shown in (a). The percentages of correct memory responses for each metamemory judgment in the unimodal haptic (left panel) and the cross-

modal visual recognition test (right panel) is shown in (b). Error bars represent 95% confidence intervals.

Next, we determined the quality of the provided metamemory judgements. Figure 2b depicts the percentages of correct memory responses for each metamemory judgment depending on the type of recognition test. In the unimodal haptic recognition test, the observed accuracy was highest for memory responses judged as remembered (*M* = 93.5%, *SD* = 5.2, 95% CI [91.9, 95.1), medium for memory responses judged as known (*M* = 78.3%, *SD* = 9.2, 95% CI [75.4, 81.2]), and lowest for memory responses judged as guessed (*M* = 65.6%; *SD* = 12.4; 95% CI [61.8, 69.4]), $t_{\text{Remember-Know}}(41) = 10.91$, $p < .001$, $d = 2.04$, 95% CI [1.46, 2.60], $t_{\text{Remember-Guess}}(42) = 16.01$, $p < .001$, $d = 2.95$, 95% CI [2.22, 3.67], and $t_{\text{Know-Guess}}(41) = 5.91$, $p < .001$, $d = 1.16$, 95% CI [0.70, 1.62]). In the cross-modal visual recognition test, a similar pattern was observed. Observed accuracy was highest for memory responses judged as remembered (*M* = 89.0%, *SD* = 10.7, 95% CI [85.7, 92.3]), medium for memory responses judged as known (*M* = 74.5%, *SD* = 12.4, 95% CI [70.6, 78.3]), and lowest for memory responses judged as guessed (*M* = 63.2%; *SD* = 11.5; 95% CI [59.7, 66.7]), $t_{\text{Remember-Know}}(41) = 7.43$, $p < .001$, $d = 1.27$, 95% CI [0.83, 1.70], $t_{\text{Remember-Guess}}(42) = 11.89$, $p < .001$, $d = 2.32$, 95% CI [1.69, 2.94], and $t_{\text{Know-Guess}}(41) = 4.64$, $p < .001$, $d = 0.94$, 95% CI [0.49, 1.38]). An analysis of variance with the factors of metamemory judgment (remember vs. know vs. guess) and type of recognition test (unimodal haptic vs. cross-modal visual) revealed no significant interaction, $F(2, 82) = 0.26$, $p = .771$, $\eta_p^2 = .01$. Comparing the percentages of correct responses for memory responses judged as guessed with chance performance (50%) revealed that memory performance was far above chance, both in the unimodal haptic recognition test, $t(42) = 8.26$, $p < .001$, $d = 1.78$, 95% CI [1.21, 2.34], and the cross-modal visual recognition test, $t(42) = 7.53$, $p < .001$, $d = 1.62$, 95% CI [1.07, 2.16].

Discussion

What is stored in long-term memory from current perceptions is a question that has attracted considerable interest. The present study reveals that humans form detailed and durable long-term memory representations for a high number of their haptic experiences, even if there is no intention to memorize them. As shown in Experiment 1, after exploring 168 everyday objects for 10 seconds each, participants showed high performance rates in a recognition memory test that required participants to distinguish between the previously explored object and a highly similar foil object. When memory was tested immediately afterwards, 94% of the previously explored objects were correctly identified; when memory was tested for the first time after one week, still 85% were correctly identified. As shown in Experiment 2, when participants haptically explored the objects without the intention to memorize them, performance in a surprise memory test after one week was still high (79%), indicating that detailed and durable long-term memory representations for haptically explored objects are stored as a natural product of haptic perception.

Beyond demonstrating that a large number of haptic experiences is stored in long-term memory, the present study reveals another interesting finding. As shown in Experiment 2, although the participants had explored the objects solely haptically and never seen before, they were able to correctly identify the objects in a one-week delayed visual recognition test with almost the same accuracy as in the haptic recognition test (73% vs. 79%). This is even more remarkable as the old and foil objects in the recognition test belonged to the same basic-level category and were only distinguishable based on the haptic experiences made during initial exploration. In particular, as an incidental encoding instruction was used, such a finding cannot be explained by intentional memorization strategies. There are two main possible explanations for this observation. First, it may be that haptic long-term memory representations are strategically retrieved at the time of the visual recognition test in order to distinguish between the elicited visual object representations. Second, it may be that visual object representations are automatically co-activated and stored when haptically exploring objects. Interestingly, the latter hypothesis is supported by evidence from brain-imaging studies, showing that cortical areas involved in visual processing seem to be activated during haptic processing as well (e.g., Snow, Strother, & Humphreys, 2014; for a review, see Lacey & Sathian, 2014). However, to clarify the exact mechanism underlying cross-modal object recognition, further research is needed.

The metamemory judgments revealed that the participants' actual memory performance was only partially accompanied by corresponding conscious metamemory experiences. Whereas most of the memory responses accompanied by the experience of recollection (remember judgment) were indeed correct, only about three out of four memory responses accompanied by the experience of familiarity (remember judgment) were correct. Furthermore, when a response in the memory test was not accompanied by an introspective metamemory experience (guess judgment), memory performance was still far above chance levels. Such a finding is in line with recent findings demonstrating the phenomenon of recognition without awareness in verbal (Craik, Rose, & Gopie, 2015) and visual memory (Kuhbandner et al., 2017; Voss, Baym & Paller, 2008), supporting speculations that there may be a perceptual long-term memory system that operates below conscious awareness (e.g., Johnson, 1983; for a review, see Higgins & Johnson, 2012). However, such an interpretation has to be treated with caution because a guess judgment may not necessarily signal unconscious memory but rather low confidence, a possibility that should be examined in future research.

The present findings parallel recent findings in the domain of visual memory. As shown in several studies, humans store also a large amount of high-fidelity representations of visually explored objects in long-term memory way (e.g., Brady et al., 2008; Konkle et al., 2010; Vogt & Magnussen, 2007) with similar durability (Andermane & Bowers, 2015) and also under incidental encoding conditions (e.g., Castelhano & Henderson, 2005; Kuhbandner et al., 2017). It has been conjectured that these findings in the visual domain challenge existing cognitive and neural models of memory storage and retrieval, which must be able to account for the large amount of stored information (Brady et al., 2008). The present findings suggest that this challenge may even be greater than initially believed because humans seem to store high-fidelity representations not only of visually but also of haptically explored objects for a relatively long period of time as a natural product of perception.

Footnotes

[1] We accidentally omitted this exclusion rule from our preregistration. However, as our aim was to examine incidental learning, excluding participants who had expected a memory test is inevitable. Including these participants revealed exactly the same results ($M_{Unimodal}$ = 79.1%, *SD* = 6.1; $M_{Cross\text{-}Modal}$ = 73.2%, *SD* = 7.5).

Author Contributions

F. Hutmacher developed the research idea and designed the experiments. F. Hutmacher and C. Kuhbandner analyzed the data and interpreted the results. F. Hutmacher and C. Kuhbandner drafted the manuscript. All authors approved the final version of the manuscript for submission.

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