Exploring the Limits of Perceptual Long-Term Memory

Kumulative Inaugural-Dissertation zur Erlangung der Doktorwürde
der Philosophischen Fakultät II
(Fakultät für Humanwissenschaften)
der Universität Regensburg

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Regensburg 2019

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Preface

This thesis presents three studies that explore the limits of perceptual long-term memory. All three studies were published in peer-reviewed journals over the last two years. They are reproduced in the accepted version with permission from the publishers. The contributions of the co-authors to the three studies are shown on page five. The reference lists of the three studies were integrated into one combined reference list at the end of this thesis. Apart from that, the manuscripts of the three studies have remained unchanged.

Contributions

Study 1 – Long-Term Memory for Haptically Explored Objects: Fidelity, Durability, Incidental Encoding, and Cross-Modal Transfer

Study idea	Fabian Hutmacher
Study design	Fabian Hutmacher
Statistical analysis	Fabian Hutmacher, Christof Kuhbandner
Manuscript writing	Fabian Hutmacher, Christof Kuhbandner
Manuscript revision	Fabian Hutmacher, Christof Kuhbandner

Study 2 – Detailed Long-Term Memory for Unattended, Irrelevant, and Incidentally Encoded Auditory Information

Study idea	Fabian Hutmacher
Study design	Fabian Hutmacher, Christof Kuhbandner
Statistical analysis	Fabian Hutmacher, Christof Kuhbandner
Manuscript writing	Fabian Hutmacher, Christof Kuhbandner
Manuscript revision	Fabian Hutmacher, Christof Kuhbandner

Study 3 – Why Is There So Much More Research on Vision Than on Any Other Sensory Modality?

Study idea	Fabian Hutmacher
Study design	Fabian Hutmacher
Statistical analysis	Fabian Hutmacher
Manuscript writing	Fabian Hutmacher
Manuscript revision	Fabian Hutmacher

1. Introduction

Right now, I am sitting in my office, desperately trying to write the introduction to my thesis. As I cannot come up with the next sentence, I look out of the window. My gaze wonders. I see a tree, the branches and leaves gently dancing in the wind, I see parked cars and parts of the university buildings, I see people passing by and craftsmen unloading materials from their van. At the same time, I am taking a sip from my cup of coffee. Then, still not knowing what to write, I scratch my head and fumble around with the pen in my hands. My fingers are gliding over the keyboard without pressing a key. When I finally have an idea that I consider worth typing down, my colleague enters the office, accompanied by a student. While they are talking about an upcoming study, going through different materials spread out on the table in front of them, I focus on my computer screen and try to ignore everything else. I write the following:

We have thousands upon thousands of perceptual experiences every day. The precise number is hard to estimate. Assuming that a third of a second is a sufficient amount of time to have a perceptual experience, and that we continuously have experiences during eight hours a day, one can calculate that a 50-year-old person has had 1,577,880,000 perceptual experiences in his or her life (see, Burnham, 1888).[1] To get a better feeling for this ungraspable number, one could also say that we have 180 experiences per minute or 10,800 experiences per hour. Although such an estimate can do nothing but to provide us with a vague rule of thumb, it gives us an impression of the amount of perceptual information that we process day in and day out. What will I remember from this perceptual input, though? What will I remember from the things that I have seen when looking outside my office window or from the things that I have touched while thinking about the next sentence? Or, asking more generally, how many of our perceptual experiences are stored in long-term memory – and how detailed are the stored memory representations? Exploring and trying to answer this question has intrigued generations of researchers. It has been speculated from early on that almost every experience is permanently stored in memory (e.g., Tetens, 1777; see also Dudai, 1997). At the same time, numerous researchers have pointed to the obvious limitations of human memory such as capacity limits for storing information.

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[1] Note, that Burnham (1888) does not use the word ‘experience’, but writes that it has been assumed that a third of a second is sufficient “for the production of one idea” (p. 72), a phrase that rather seems to refer to thoughts than to perceptual experiences. However, the calculation reported above can be used for estimating the number of perceptual experiences as well. That one only makes experiences during eight hours per day was an assumption made to account for “sleep, etc.” (p. 72).

Against this background, the first section of the introduction briefly reviews arguments against detailed memory representations in perceptual long-term memory, anecdotal evidence supporting the idea that humans may be able to store more information than commonly assumed, and previous studies demonstrating that memories stored in perceptual long-term memory are indeed more durable and more detailed than previously believed. As the existing studies are almost exclusively studies on *visual* long-term memory, the question arises whether the results obtained for visual long-term memory hold true for other sensory modalities. Thus, the goal of **Study 1** was to investigate the quantity and quality of information stored in *haptic* long-term memory.

Exploring the similarities and differences between the sensory modalities when it comes to storing perceptual experiences is only one way of approaching the question of how many of the perceptual experiences we make are stored in long-term memory. Another way of doing this is to consider the role of attention. It is commonly accepted that the processing of attended information is enhanced compared to the processing of unattended information (for a review, see Serences & Kastner, 2014). Thus, I will probably be better at recalling the color of the parked cars in front of my window I have attentively looked at than at recalling the color of the dress of the student my colleague was talking to while I was trying to focus on writing this introduction. What happens to the unattended information, though? As described in the second section of the introduction, it is argued that unattended information is filtered out at some stage of the processing hierarchy, leaving no trace in long-term memory, at least if the attentional resources are fully exhausted. Simply put, I may remember the color of the student's dress, but only if I did not manage to focus completely on working on the introduction. **Study 2** was designed to challenge this assumption and to demonstrate detailed long-term memory for unattended, irrelevant, and incidentally encoded auditory information. In addition, Study 2 investigated whether the finding that detailed perceptual long-term representations are stored for visual as well as for haptically explored material (as demonstrated in Study1) can also be extended to auditory information.

As the introductory paragraph has illustrated, we permanently make perceptual experiences with all our senses: vision and hearing as well as touch, smell, and taste. However, as already briefly mentioned above, most research about perceptual long-term memory is research about *visual* long-term memory. More generally speaking, vision is the most studied sensory modality. This bias towards vision needs an explanation. **Study 3** attempts to provide such an explanation, or rather: to weigh different explanations against each other. The theoretical background for this study is sketched in the third section of the introduction. The fourth section summarizes the research questions.

1.1 The Quantity and Quality of Information Stored in Perceptual Long-Term Memory

The introductory paragraphs used the term ‘perceptual experience’ without defining it. So what is a perceptual experience? First, a perceptual experience is not the same as a sensation. While ‘sensation’ refers to the detection of stimuli in the environment by the receptors of our senses as well as the transduction of this stimulation into electrical impulses, ‘perception’ refers to the process of interpreting sensory information to understand and to represent the outside world (see, e.g., Goldstein, 2010). Second, a perceptual experience is not necessarily a conscious experience. When riding a bike over a bumpy road, for instance, you will be aware of the fact that you need to balance yourself in order not to fall down. The incoming information used to achieve this, and the perceptions that lead to a specific motor action, normally remain beyond conscious awareness. Thus, a perceptual experience is the conscious or unconscious perception of stimuli from our environment. In this context, perceptual long-term memory can be defined as long-term memory for the perceptual aspects of information reaching our senses in contrast to the semantic or conceptual aspects, no matter whether we are consciously aware of the stored perceptual information or not (see, e.g., Schacter, 1990; Johnson, 1983; 2007). To give an illustrative example, perceptual memory is memory for the shape or the color of the cars parked in front of my window; it is memory for the perceptual features of these cars as well as the combination of these features. Remembering or recognizing the brand or even the specific product line of the car is not part of perceptual memory, but part of semantic or conceptual memory. Bearing this in mind the question arises: What is stored in long-term memory from current sensations on a perceptual level?[2]

At first, one may point to some of the obvious limitations of human visual perception and perceptual memory. Let us begin with the physiological constraints: While we have the impression of perceiving a rich and detailed world, only a fraction of our visual field is represented in high resolution, while non-foveated, peripheral information is represented in reduced fidelity (see, e.g., Cohen, Dennett, & Kanwisher, 2016; Rosenholtz, 2011). Apart from

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[2] Note, that the following remarks are almost exclusively based on studies and observations involving *visual* memory. This is simply because most studies on perceptual memory are studies on *visual* perceptual memory. The reasons for this are discussed in Study 3. Studies 1 and 2 can be seen as attempts to gain insight into the functioning of haptic (Study 1) and auditory (Study 2) perceptual long-term memory.

this, there seem to be limits for processing and remembering perceptual information at the different stages of visual processing. Take *iconic memory*, for instance: It has been demonstrated that humans are capable of storing incoming visual information in high resolution for a very short time only – a couple hundred of milliseconds (Sperling, 1960). While the immediate sensory impression remains visible after the stimulus has disappeared for about 80-100 ms (*visible persistence*; Di Lollo, 1980), a non-visible sensory trace containing the informational value of the input is stored for about 150-300 ms (*informational persistence*; Irwin & Yeomans, 1986). The information that has not faded away after the first couple hundred of milliseconds can be transferred to *visual working memory*, which enables us to actively maintain information for several seconds in order to deal with ongoing tasks (e.g., Baddeley & Hitch, 1974; Cowan, 2008; Ma, Husain, & Bays, 2014).

However, the resources of visual working memory are believed to be severely limited. While the proponents of *fixed slot models* (see, e.g., Awh, Barton, & Vogel, 2007; Drew & Vogel, 2008; Luck & Vogel, 1997; 2013; Zhang, & Luck, 2008) assume that visual working memory capacity is restricted to maintaining a small and fixed number of objects, such as Cowan's (2001) 'magical number four' (for more recent capacity estimates see, e.g., Franconeri, Alvarez, & Enns, 2007; Howe, Cohen, Pinto, & Horowitz, 2010), proponents of *continuous resource models* have tried to demonstrate that visual working memory capacity is not so much restricted by the number of objects but by the amount of information, which can be retained (see, e.g., Alvarez, & Cavanagh, 2004; Bays & Husain, 2008; Franconeri, Alvarez, & Cavanagh, 2013; Wilken & Ma, 2004). Although there is an ongoing debate about which kind of model provides a better description of visual working memory capacity, and although a new kind of model emerged over the past few years, trying to provide a middle ground between slot and resource models (so-called *flexible slot models*, see, e.g., Dyrholm, Kyllingsbæk, Espeseth, & Bundesen, 2011; Sims, Jacobs, & Knill, 2012; van den Berg, Awh, & Ma, 2014) all models share the assumption that only a fraction of the incoming perceptual information can be actively maintained.

If perceptual memory is already limited at the earlier processing stages, it seems plausible to speculate that perceptual *long-term* memory is also limited. This consideration is supported by two related phenomena: *change blindness* and *inattentional amnesia*. The term 'change blindness' refers to the fact that observers often miss even significant changes within a visual scene, when the presentation of the changed and the unchanged version of the scene is either briefly interrupted (O'Regan, Rensink, & Clark, 1999; Rensink, O'Regan, & Clark, 1997) or the change occurs gradually (Simons, Franconeri, & Reimer, 2000). This has been taken as evidence that “observers never form a complete, detailed representation of their surroundings” (Rensink et al., 1997, p. 368; for reviews on change blindness see, e.g., Jensen, Yao, Street, & Simons, 2011; Rensink, 2002; 2008; Simons & Ambinder, 2005).[3] The second phenomenon, inattentional amnesia, is linked to the same limitations of human perception and memory, but in a slightly different manner: When observing a scene, people miss parts of the very scene they are not attending to. In probably the most famous study on the topic, participants were asked to count the number of times a basketball was passed but while doing so, they did not notice that a person in a gorilla costume was walking through the scene (Simons & Chabris, 1999). Taken together, the above-mentioned theories and the observations regarding change blindness and inattentional amnesia have “led to the widely accepted idea that memory representations for real-world stimuli are impoverished and lacked [*sic*] visual detail” (Brady, Konkle, & Alvarez, 2011, p. 14). Everything that was said so far is summarized by Brady, Konkle, Alvarez, and Oliva (2008) as follows: “[W]ithin a few hundred milliseconds of perceiving an image, sensory memory confers a truly photographic experience, enabling you to report any of the image details. Seconds later, short-term memory enables you to report only sparse details from the image. Days later, you might be able to report only the gist of what you had seen” (p. 14325).

However, the view that only the gist of prior perceptual input is stored in perceptual long-term memory can be challenged in two ways. First, by pointing to anecdotal evidence reporting exceptional memory abilities for at least some humans. Second, by considering empirical evidence accumulated over the last decade. Let us begin with the anecdotal evidence. One group of people that has been associated with exceptional memory abilities are *savants* (for an overview see, e.g., Happé & Frith, 2009; Treffert, 1989; 2009; Treffert &

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[3] Interestingly, the argument that phenomena like change blindness and inattentional amnesia demonstrate that observers never form a complete, detailed representation of their surroundings has been questioned for at least two reasons. First, it has been noted that “the existence of change blindness does not on its own necessitate sparse representations – it could occur even with fairly detailed and complete visual representations of a scene” (Simons & Rensink, 2005, p. 18). Second, there are a number of studies demonstrating that participants may be able to detect changes in a visual scene although they are explicitly unaware of this ability (see, e.g., Fernandez-Duque & Thornton, 2000; 2003; Laloyaux, Destrebecqz, & Cleeremans, 2006; Laloyaux, Devue, Doyen, David, & Cleeremans, 2008; Thornton & Fernandez-Duque, 2000). In other words, relying on explicit reports may underestimate the fidelity of representations in human perceptual memory.

Wallace, 2002): Savants are people that show brilliant skills in one domain while being severely limited in (all) other intellectual domains.[4] Often, the outstanding, brilliant skill of savants is a memory skill. Kim Peek, for instance, was able to memorize a book page by heart in about eight to ten seconds (Treffert & Christensen, 2005). Another famous example for savant skills is Stephen Wiltshire, who is able to create extremely accurate and extremely detailed drawings of what he has seen before – and not only from small-range visual scenes, but even from whole cities (Sacks, 1995). The reasons for these outstanding abilities are still debated: While some argue that savants have a detail-focused processing bias (Happé & Vital, 2009), others believe that they are outstandingly good at recognizing repeating patterns and show a general tendency towards sensory hypersensitivity (Baron-Cohen, Ashwin, Ashwin, Tavassoli, & Chakrabarti, 2009; Mottron, Dawson, & Soulières, 2009). In fact, it seems likely that different people with savant skills may profit from interindividually varying mechanisms so that the term 'savant' should perhaps rather be seen as an umbrella term, encompassing different kinds of outstanding abilities (see, e.g., Grandin, 2009, for a personal account).

There are at least two more groups of people who have been associated with excellent perceptual memory skills: people with a so-called *highly superior autobiographical memory* (HSAM) and people with *eidetic memory*. In short, individuals with HSAM show "the ability to recall accurately vast amounts of remote salient autobiographical events without the explicit use of mnemonics" (LePort, Stark, McCaugh, & Stark, 2016, p. 1; see also LePort et al., 2012; LePort, Stark, McCaugh, & Stark, 2017; Parker, Cahill, & McCaugh, 2006; Patihis et al., 2013). A. J., the first person who was reported having HSAM skills describes her memory abilities as follows: "I think about the past all the time … It's like a running movie that never stops. It's like a split screen. I'll be talking to someone and seeing something else …" (quoted in Parker et al., 2006, p. 35). Interestingly, individuals with HSAM do not show any advantage over age-and sex-matched controls on standard working memory tests (LePort et al., 2012; LePort et al., 2017). Thus, what distinguishes individuals with HSAM from people with average memory skills seems to be the ability to *explicitly remember* more information over a longer period of time rather than the ability to attentively *process* more information in the present moment (LePort et al., 2016). Additionally, the advantage regarding the remembering of information seems not to apply to just any kind of information, but

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[4] Savant syndrome is often associated with autistic spectrum disorders. Note, however, that "not all autistic persons have savant syndrome and not all persons with savant syndrome have autistic disorder" (Treffert, 2009, p. 1353).

"relatively selectively, [to the] recollection of personal, autobiographical material" (LePort et al., 2017, p. 276). Possible explanations for this advantage are still discussed, ranging from neuroanatomical differences (LePort et al., 2012) over the extensive, almost obsessive rehearsal of autobiographical information (LePort et al., 2016) to the use of special reconstructive processes and strategies (Patihis et al., 2013).

Most research on eidetic memory was conducted in the 1960s and 1970s and explored the eidetic memory skills of children (for a review of these efforts see Haber, 1979; for a critical discussion of some key issues see also Giray, Altkin, Roodin, & Vaught, 1977; Gray & Gummerman, 1975; for the rare case of an adult eidetiker see Stromeyer, 1970; Stromeyer & Psotka, 1970, but see also Blakemore, Braddick, & Gregory, 1970 and Merritt, 1979 for a critical discussion of the case). Depending on the study, between 2 and 15 percent of elementary-school-aged children have been found to possess eidetic memory skills (Haber, 1979), that is, the ability to continue seeing an image for up to several minutes after the physical stimulus has been removed. Then, the image starts to fade away gradually. It seems that eidetic memory is more frequent in younger than in older children (Richardson & Harris, 1986; but see Haber & Haber, 1988), an age trend for which different reasons have been discussed. While it is possible that eidetic memory fulfills a developmental role as it enables children to inspect and rehearse a visual stimulus for a longer time before transferring it to long-term memory (Giray et al., 1977), one could also assume that the ability is "a leftover from an earlier less-differentiated level of cognitive organization" (Richardson & Harris, 1986, p. 307). Put another way, children's perception of the world may be less driven by a top-down modulated, conceptual mindset; instead, children may put greater emphasis on the perceptual dimension of the incoming information (Searleman & Herrmann, 1994; for a recent study see Plebanek & Sloutsky, 2017).

All the groups described above differ in some respect from what is considered 'normal' or at least 'average'. Thus, it remains unclear what exactly can be learned from examples of people with extraordinary memory skills. Their skills may be 'extraordinary' in the sense that those people are capable of doing something most others are absolutely unable to do, that is, that they possess abilities that differ *qualitatively* from those of 'normal', average adults. However, it is also possible that the 'extraordinary' memory skills are not that extraordinary after all, and that the difference is rather *quantitative* than qualitative. In this context, one may speculate, for instance, that the enhanced perceptual processing observed in people with savant skills (see above) may be present in all of us at least to a certain degree, that is, that our more conceptual processing style masks our perceptual abilities, and that we do in fact store more detailed memories of the perceptual input than previously believed.

As it seems impossible to draw any clear-cut conclusions from the anecdotal observations presented here, it is advisable to take a closer look at the available empirical evidence that has accumulated over the last decades (for a review, see, e.g., Brady, Konkle, & Alvarez, 2011). Landmark studies from the late 1960s and early 1970s have demonstrated that humans are able to store huge quantities of visual information (Shepard, 1967; Standing, 1973; Standing, Conezio, & Haber, 1970). In his seminal study, Standing (1973) presented 10,000 colored images over five consecutive days at a rate of 5 seconds per picture and with an interstimulus interval of 600 milliseconds to his participants. Based on the performance of the participants in a memory test two days after the presentation of the images, it was estimated that participants successfully remembered about 6,600 of the presented 10,000 pictures. These results "have led many to infer that the number of visual items that can be stored in long-term memory is effectively unlimited" (Brady et al., 2011, p. 13). However, the studies mentioned so far only allow for conclusions regarding the *quantity* and not so much for conclusions regarding the *fidelity* or *quality* of the stored representations.

This has changed during the last decade (see, e.g., Brady et al., 2008; Hollingworth, 2004, 2005; Hollingworth & Henderson, 2002; Vogt & Magnussen, 2007). In a study conducted by Vogt and Magnussen (2007), for instance, participants viewed 400 pictures of doors for 5 seconds each. Memory for these pictures was tested at four different time intervals ranging from thirty minutes to one week, with a two-alternative forced choice test (2AFC) consisting of a picture that had been presented in the study phase and a novel picture. Crucially, for half of the participants, not the *original*, but an *edited* version of the pictures was used during study and test. In the edited version, all features of the pictures unrelated to the doors (such as signs, doorbell panels, etc.) were removed. However, memory was significantly better for the original pictures, demonstrating that participants did not only store the gist of the images.

These results were confirmed and extended by Brady et al. (2008): Participants viewed 2,500 categorically distinct everyday objects for 3 seconds each. Memory for these objects was tested in a 2AFC in one of three conditions: in the *novel condition* (comparable to the test used by Standing, 1973), participants had to indicate which of two different objects they had seen before (e.g., a bar of soap or an apple); in the *exemplar condition*, participants had to choose between two objects from the same basic-level category (e.g., two apples); in the *state condition*, participants had to choose between two states of the same object (e.g., a complete apple or an apple from which someone has taken a bite). Participants performed comparably well in all three conditions (*novel*: 93% correct, *exemplar*: 88%, *state*: 87%), indicating that visual long-term memory has a massive storage capacity for object details. These results were replicated for shorter presentation times (Brady, Konkle, Oliva, & Alvarez, 2009) and when the images were unattended (Kuhbandner, Rosas-Corona, & Spachtholz, 2017), as well as for different stimulus material such as visual scenes (Konkle, Brady, Alvarez, & Oliva, 2010) and movements (Urgolites & Wood, 2013).

While these studies have shown that representations in *visual* perceptual long-term memory are more detailed than previously believed and that humans seem to store more than the gist of incoming visual information, relatively little is known about perceptual long-term memory for perceptual information from other modalities such as touch (for the reasons behind this see the third section of the introduction as well as Study 3). Most existing studies on haptic long-term memory used retention intervals in the range of several minutes (see, e.g., Ballesteros, Reales, & Manga, 1999; Ballesteros & Reales, 2004; Craddock & Lawson, 2008; Gadelha, Fernández-Calvo, Ferreira, de Jesus Marques, & dos Santos, 2016; Sebastián, Reales, & Ballesteros, 2011). However, it seems that memory for haptically explored objects prevails for at least one week (Pensky, Johnson, Haag, & Homa, 2008). Thus, one may speculate that the quantity of information that can be stored in haptic long-term memory is effectively unlimited – just like the quantity of information that can be stored in visual long-term memory. Nonetheless, it is important to find out more about the *fidelity* of information stored in haptic long-term memory: Demonstrating that perceptual experiences in other sensory modalities – such as touch – are stored in similar quantity and quality as visual experiences, would challenge existing models on the functioning of human memory, which assume that that perceptual long-term memory representations are rather sparse and that most perceptual input is rapidly forgotten (see, e.g., Brady et al., 2008). Thus, Study 1 explored the limits of haptic long-term memory regarding the durability and fidelity of memory representations. Additionally, Study 1 investigated the effects of incidental encoding on the quality of the stored memory representations as well as the limits of crossmodal transfer, that is, the ability to recognize haptically explored objects in a visual memory test.

1.2 The Fate of Unattended Information

Remember the scene described in the beginning of the introduction: In every moment of our lives, we are confronted with a vast amount of sensory information. Due to the limits of human cognition, we are not capable of processing all of this information intensively. The means by which we actively select the information that needs to be processed in a given moment is attention (Sternberg & Sternberg, 2017). What is attention? According to William James (1890/1950), the answer is quite simple:

> Every one knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others […]. (p. 403-404)

Expressed more technically, attention helps us to respond quickly and accurately to the relevant stimuli in our environment while ignoring the irrelevant rest (for classic experimental evidence see, e.g., Egly, Driver & Rafal, 1994; Posner, Nissen, & Ogden, 1978). Which stimuli we consider to be relevant depends on our current goals and individual interests (e.g., Castelhano & Henderson, 2008; Noton & Stark, 1971; Yarbus, 1967) as well as our prior knowledge (e.g., Võ & Henderson, 2009), but also on the salience of the stimuli (e.g., Theeuwes, 1992).

Thus, the enhanced processing of attended compared to unattended information seems to be commonly accepted (for a review, see, e.g., Serences & Kastner, 2014). But what about the unattended information? Will I remember the dress of the student my colleague was talking to while I was trying to focus on writing this introduction – or will all the information about her dress be pushed into oblivion because I did not attend to it? In short, models of selective attention strongly lean towards the second option, that is, they state that unattended information is filtered out at some stage of the processing hierarchy and thus not stored in long-term memory – at least if the attentional load is high enough, that is, if the attentional resources are fully exhausted (see, e.g., Lavie, 2005, 2010; for a more extended discussion of the differences between early and late selection models see the introduction of Study 2). Study 2 was designed to challenge this assumption by demonstrating that detailed memory representations are stored in perceptual long-term memory even when the incoming perceptual information is completely unattended, irrelevant for the current task, and incidentally encoded. Together with Study 1, Study 2 challenges common assumptions about perceptual long-term memory. First, the assumption that perceptual long-term memory representations are rather sparse, that is, that they lack detail and contain only the gist of the incoming perceptual information. Second, the assumption that storing detailed perceptual long-term memory representations is an effortful process that crucially depends on the allocation of attention to the stimuli as well as the intention to memorize them. Thus, showing that detailed memory representations are stored as a natural product of perception would challenge common models of memory storage and retrieval.

1.3 Perception and Memory Are (Not) All About Vision

If you open the textbook on *Sensation and Perception* by Goldstein and Brockmole (2017) and take a look at the table of contents, you will realize that six chapters are explicitly dedicated to vision ("Perceiving Objects and Scenes", "Visual Attention", "Taking Action", "Perceiving Motion", "Perceiving Color", "Perceiving Depth and Size"), while three are dedicated to hearing ("Hearing", "Hearing II: Location and Organization", "Speech Perception"), one to touch ("The Cutaneous Senses"), and one to taste and smell combined ("The Chemical Senses"). Interestingly, four more chapters that are meant to explain some general principles about sensation and perception ("Introduction to Perception", "The Beginning of the Perceptual Process", "Neural Processing", "Cortical Organization"), almost exclusively use examples from vision to illustrate these principles and could thus be counted as "visual" chapters as well. No matter whether counting the number of chapters or the number of pages dedicated to each sensory modality (vision: 166 pages or 256 when counting the first four chapters as visual chapters, hearing: 78 pages, touch: 24 pages, taste and smell: 23 pages), the conclusion remains the same: The part of the book dealing with aspects of vision is longer than the part of the book dealing with all other sensory modalities combined.

This bias towards vision is not a peculiarity of the book by Goldstein and Brockmole (2017), but can be found in many – if not all – other textbooks on perception and perceptual memory (see, e.g., Kandel, Schwartz, & Jessell, 2000; Sternberg & Sternberg, 2017). However, the dominance of the visual is not even restricted to psychology textbooks or research on perceptual memory (see Gallace & Spence, 2009), but can be found in everyday life as well. Take the regulations for private accident insurance companies in Germany, for instance, as published by the German Insurance Federation (Gesamtverband der Deutschen Versicherungswirtschaft, 2019). After an accident, the degree of disability is evaluated (0-100%). As the German Insurance Federation explains, the degree of disability depends on how much a certain disability affects 'everyday performance'. The insurance company has to pay the respective fraction of the sum insured. The regulation states the following degrees of disability for the loss of the different senses: both eyes: 100%, one eye: 50%, hearing in both ears: 60%, hearing in one ear: 30%, smell: 10%, taste: 5%. The sense of touch is not explicitly mentioned in this list. However, this should probably not be taken as evidence that the loss of touch would not significantly impair peoples' lives. Rather, it may simply be because it is hard to imagine how one could *completely* lose the ability to perceive touch – although one may very well experience a loss of sensibility in certain body parts (for the rare case of congenital insensitivity to pain see the respective section of Study 3). In this context, one may consider the degree of disability assigned to the loss of different parts of one's extremities, keeping in mind that the loss of a body part is certainly different from merely losing sensibility in one of these body parts. That being said, the German Insurance Foundation assigns a degree of disability of 70% to the loss of an arm or a leg, 40% to the loss of a foot, 20% to the loss of the thumb, 10% to the loss of the index finger, and 5% to the loss of any other finger. According to these numbers, no loss is worse than the loss of sight in both eyes. Thus, all in all, the regulations published by the German Insurance Foundation confirm the observations reported above: Vision seems to be the dominant sense – both in research and in public perception.

The question is: Why? Why is there so much more research on vision than on any other sensory modality – although we permanently make perceptual experiences with all our senses? At first, one may think that this question is relatively easy (and may even be trivial) to answer: Is vision not simply our most important sense, is it not the sense that we would miss the most if we lost it? If so, the bias towards vision in research would mirror the natural importance of vision in our daily lives. Although there may be arguments in favor of this straightforward explanation, one should not forget that research agendas are not necessarily driven by rational reasons, but often rather depend on idiosyncratic circumstances (see, e.g., Feyerabend, 1975; Kuhn, 1962). Thus, it does not only seem to be legitimate, but advisable, to look for reasons beyond the idea of the natural importance that can help explain the bias towards vision in research. This is done in Study 3. In case it should turn out that at least the degree to which vision dominates research on perception and perceptual long-term memory cannot solely be explained by pointing to its natural importance, this would open up a space for reflecting upon the relevance of the other senses and about the way future research agendas should be designed.

1.4 Study Overview and Summary of the Research Questions

Study 1 investigated the quantity and quality of information stored in haptic-long term memory. Study 1 was divided into two experiments. In Experiment 1, participants haptically explored 168 everyday objects for ten seconds per object. Participants were asked to remember the objects for a later memory test. Half of the objects were tested immediately after exploration, the other half one week later. In order to show that detailed memory representations were stored, memory for the objects was tested with a 2AFC in which participants had to indicate which of two objects from the same basic-level category (e.g., two different sports shoes, two different hammers) they had explored before. Participants were blindfolded during exploration and test. Experiment 2 used the same basic design with four crucial changes. First, encoding was incidental, that is, participants did not know that their memory for the explored objects would be tested later. Second, half of the haptically explored objects were tested in a crossmodal visual test. Third, participants were asked to provide metamemory judgments at test. Fourth, memory for all objects was tested after one week. Again, participants were blindfolded during exploration and during the unimodal haptic test. Participants were not allowed to touch the objects during the crossmodal visual test.

Study 2 was designed to challenge the assumption that no information is stored in long-term memory when the attentional resources are fully exhausted by a concurrent task and to test whether detailed memory representations are stored in perceptual long-term memory for auditory information. While viewing a rapid visual stream of words and reacting to direct word repetitions, participants were simultaneously presented with an auditory stream consisting of everyday sounds. Participants were told that the sounds were irrelevant and that they should try to avoid distraction by the sounds as much as possible. Memory for the unattended, irrelevant, and incidentally encoded sounds was tested in a surprise memory test. Memory was tested using a 2AFC. Participants had to choose between two sounds from the same basic-level category (e.g., the humming of two different refrigerators). Half of the sounds was tested in an immediate test; the other half was tested one day later. Above-chance performance would indicate that detailed information was stored in auditory perceptual long-term memory, even though the attentional demands were high and participants were fully distracted by stimulation in a different sensory modality.

Although the first two studies of this thesis are concerned with haptic and auditory long-term memory respectively, most research on perceptual long-term memory is research on *visual* long-term memory. **Study 3** investigated the reasons behind this apparent dominance of the visual. Intuitively, one may think that the dominance of the visual is easy to explain: Researchers and lay people alike seem to be convinced that vision is not only the most important, but also the most complex of our senses. Thus, the dominance of the visual would merely mirror the functioning of human brains and bodies. Before accepting this conclusion, however, one should take a closer look at the claim that vision is our most important and most complex sensory modality. Study 3 does so by analyzing different definitions of the terms ‘importance’ and ‘complexity’. In addition, one should also look for alternative explanations that can help understand the dominance of the visual. This is done by investigating possible methodological, structural, and cultural mechanisms maintaining and supporting the bias towards vision. In case it should turn out that the dominance of the visual is not simply a law of nature, but influenced by human-decision making, one could start thinking about whether the degree to which vision dominates research on the senses is actually desirable.

2. Peer-Reviewed Studies

2.1 Study 1 – Long-Term Memory for Haptically Explored Objects: Fidelity, Durability, Incidental Encoding, and Cross-Modal Transfer

This is a pre-copy-editing, author-produced version of an article published 2018 in Psychological Science following peer review. The official citation that should be used in referencing this material is Hutmacher, F. & Kuhbandner, C. (2018). Long-Term Memory for Haptically Explored Objects: Fidelity, Durability, Incidental Encoding, and Cross-Modal Transfer. *Psychological Science, 29*, 2031-2038. Copyright © 2018 The Author(s). doi: 10.1177/0956797618803644

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.

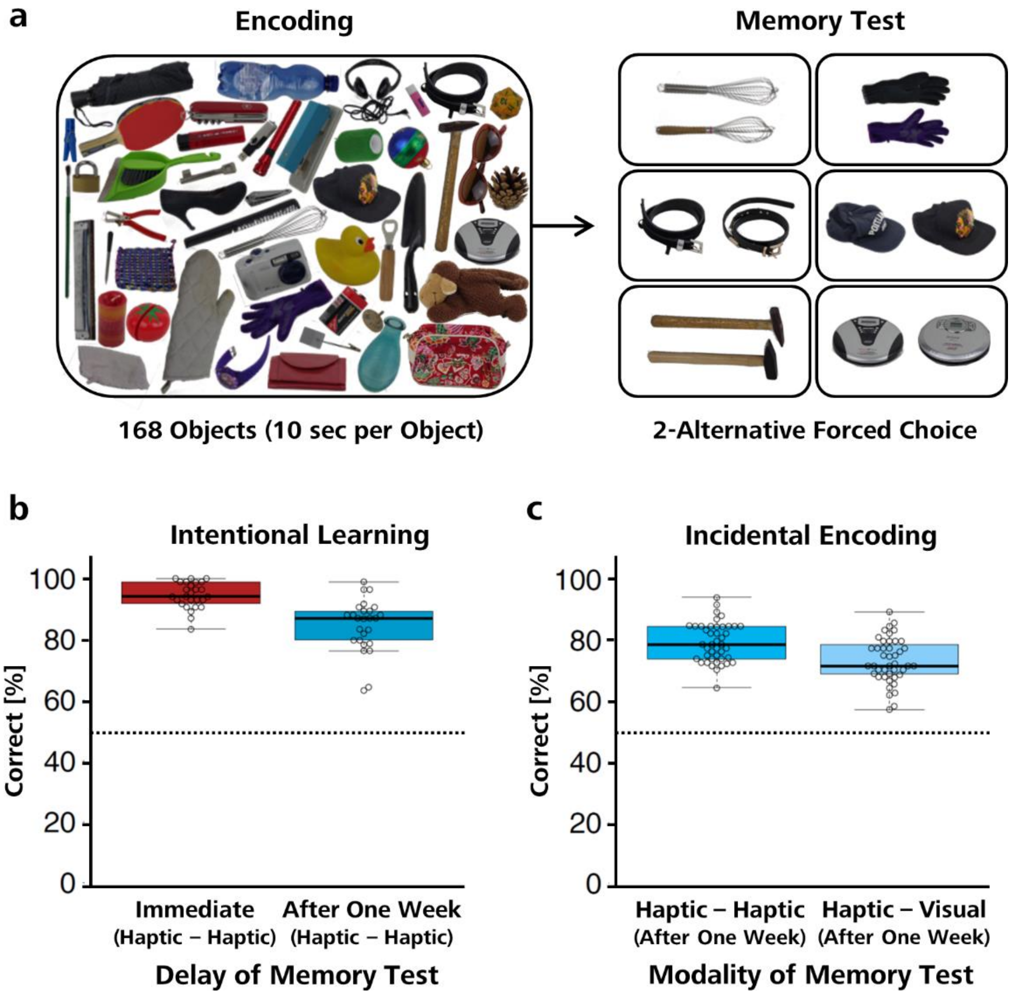

Figure 1. **Memory paradigm and recognition performance**. The procedure of Experiments 1 and 2 is illustrated in (a). In an initial encoding phase, blindfolded participants haptically explored 168 everyday objects for 10 seconds each. Subsequently, memory was tested using a two-alternative forced-choice 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].

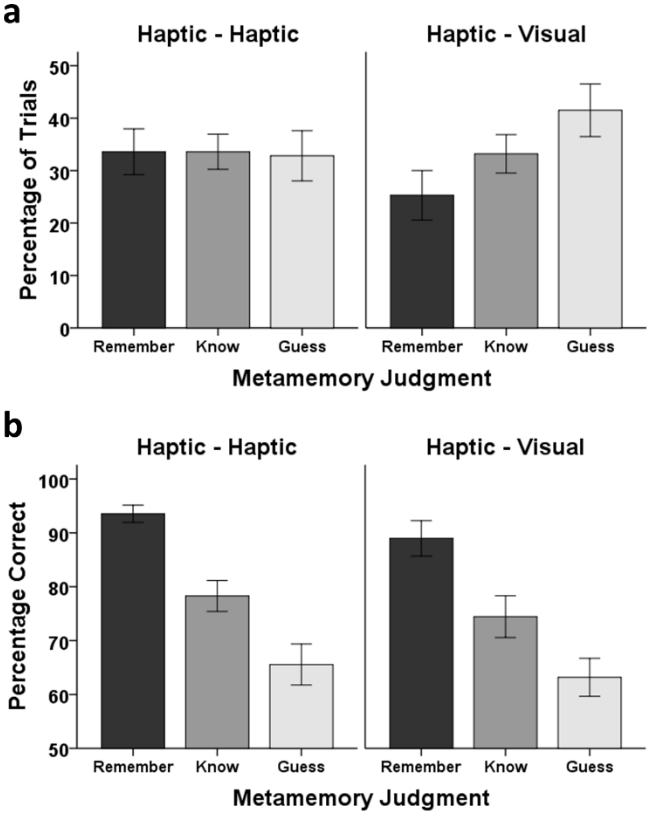

Figure 2. **Metamemory Judgments in Experiment 2**. The percentages of memory responses rated as remembered, known, or guessed in the unimodal haptic (left panel) and the cross-modal visual recognition test (right panel) is shown in (a). The percentages of correct memory responses for each metamemory 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; $M_{\text{Cross-Modal}}$ = 73.2%, SD = 7.5).

2.2 Study 2 – Detailed Long-Term Memory for Unattended, Irrelevant, and Incidentally Encoded Auditory Information

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Abstract

At any moment, a myriad of information reaches our senses, of which only a small fraction is attentively processed. A long held believe is that unattended information is only weakly processed if attentional demands are high and the unattended information is irrelevant, leaving no recognizable trace in long-term memory. The present study challenges this assumption. Participants (N = 51) were simultaneously presented with a rapid visual stream of words and an auditory stream of everyday sounds, with the instruction to attend to the visual stream and detect word repetitions, and to avoid distraction by the irrelevant sounds. No mention was made that their memory would be tested later. Memory for the sounds was tested in a surprise two-alternative forced choice recognition test with similar foil sounds. Half of the sounds were tested immediately after encoding, the other half after a delay of 24 hours. Memory performance was substantially above chance in both the immediate and the 24-hours delayed test, without significant forgetting across time. These results demonstrate that detailed and durable long-term memory representations are formed for unattended and irrelevant information that is incidentally encoded in a different sensory modality than the attended information.

Keywords: perceptual long-term memory, auditory long-term memory, long-term memory capacity, attention, attentional load

Detailed Long-Term Memory for Unattended, Irrelevant, and Incidentally Encoded Auditory Information

Imagine you are sitting in a café, engaged in a conversation with a friend that fully captures your attention. At the table behind you, somebody fills a glass with water from a bottle, producing a sound that reaches your auditory senses but is not noticed by you. One day later, somebody unexpectedly asks you about your memory for the perceptual details of the sound. Would you be able to recognize the perceptual details despite not having noticed the sound the day before? The aim of the present study was to examine this question.

At any moment, a vast amount of information reaches our senses, of which only a small fraction is relevant for our current goals. In order to behave in a functional way, our cognitive system needs to attend to the relevant fraction of the incoming information. Furthermore, since capacity is limited at several stages of the processing hierarchy (e.g., Cowan, 2001; Luck & Vogel, 1997), processing at these limited-capacity stages should be focused on the attended information as well. Thus, it seems to be a natural necessity of functional behavior that only a part of the incoming information is attended and processed in an enhanced way, an assumption that is supported by an abundance of empirical findings (for a review, see Serences & Kastner, 2014).

However, while the enhanced processing of attended information seems to be a settled fact, the fate of the unattended information is still debated, although this has received considerable research attention for several decades (for reviews, see, e.g., Driver, 2001; Lavie, 2006). Initially, at the heart of the debate was the question at which stage of the processing hierarchy unattended information is filtered out. According to early selection accounts (Broadbent, 1958), unattended information is initially represented in the form of low-level feature representations but does not reach subsequent processing stages where feature representations are integrated into coherent objects and represented in semantically meaningful ways. In contrast, according to late selection accounts (Deutsch & Deutsch, 1963), both attended and unattended information is processed in parallel up to the levels of object perception and semantic description. Attention operates after completion of these processing stages, selecting a subset of the processed items that is further processed in working memory and consciously perceived, filtering out processed items that are not selected.

As empirical findings did not reveal a clear picture in favor for either early or late selection, more flexible models have been suggested. For instance, according to attentional-load accounts (Lavie, 1995; 2010), the stage at which unattended information is filtered out varies as a function of the demands that are imposed by a task on perceptual capacity. If a task imposes high demands that exceed capacity limits, only task-relevant items are processed so that early selection occurs. If a task imposes only low demands, the remaining capacity spills over to task-irrelevant items that are then processed at higher levels as well. Taken together, the existing findings are best interpreted in terms of a flexible multi-level account, suggesting that unattended stimuli are filtered out at different stages in the processing hierarchy, depending on the specific demands of a task (e.g., Serences & Kastner, 2014).

One common assumption that is shared by all of the mentioned accounts is that unattended information is filtered out somewhere during the processing hierarchy, at least if the attentional demands of a task are high enough, suggesting that unattended information does not reach the stage of long-term memory storage. In fact, such an assumption was initially supported by numerous empirical studies showing that unattended information is not consciously remembered (e.g., Glucksberg & Cowen, 1970; Norman, 1969; Peterson, 1964). However, in the course of the discovery of the phenomenon of the existence of unconscious implicit memory, this view has been challenged. Using tasks such as word-fragment completion or perceptual identification, it has been shown that past experiences can affect current thoughts and behaviors without any awareness that one is influenced by memories of past experiences (e.g., Schacter, 1987; for a review see Schacter, Chiu, & Ochsner, 1993). In particular, such effects have been shown to occur even after very long retention intervals of several days (Musen & Treisman, 1990), months (Mitchell & Brown, 1988), or even years (Mitchell, 2006).

Thus, since conscious awareness seems not to be a necessary precondition of memory, it may be that even unattended information that does not reach the stage of conscious perception during initial encoding is stored in long-term memory. In fact, such an assumption seems to be supported by a number of studies showing that dividing attention during encoding does substantially reduce performance on explicit memory tests that require conscious recollection of previous experiences (e.g., free or cued recall) but not on implicit memory tests that do not rely on conscious recollection (e.g., Mulligan, 1998), suggesting that the withdrawal of attention during initial encoding does not decrease subsequent implicit memories. In particular, as shown in more recent studies, withdrawing attention from to-be-studied items seems sometimes even to enhance the ability to perceptually identify the items later (Voss, Baym, & Paller, 2008).

However, there are two problems with the mentioned studies in the domain of implicit memory that make it difficult to draw conclusions about the fate of unattended information. First, although the studied items were “unattended” in the sense of withdrawal of attention by a concurrently performed task, the “unattended” items were still relevant stimuli for the participants because no incidental encoding instructions were used. Second, although relatively attention-demanding secondary tasks were used (e.g., concurrently monitoring up to seven digits; Mulligan, 1998), it may be that perceptual capacity was not fully exhausted by the secondary task so that attentional resources may have spilled over to the to-be-studied items, which seems to be likely as these items were not deemed as irrelevant.

In fact, several subsequent studies have consistently demonstrated that observers show a null memory effect for unattended stimuli in a subsequent old-new recognition (ONR) test, when incidental encoding instructions are used in combination with a high attentional load task (i.e., monitoring of a rapid continuous presentation of to-be-attended stimuli; Butler & Klein, 2009; Hoffman, Bein, & Maril, 2011; Lavie, Lin, Zokaei, & Thoma, 2009; Rees, Russell, Frith, & Driver, 1999; Ruz, Wolmetz, Tudela, & McCandliss, 2005; Ruz, Worden, Tudela, & McCandliss, 2005). Thus, it seems that unattended irrelevant information is not stored in long-term memory when the attentional load of the attended task is high enough.

However, this has been challenged by a number of recent studies in which the same high attentional load task was used as in the previous studies, but in which memory was assessed with more sensitive memory tests (Butler & Klein, 2009; Hoffman, Bein, & Maril, 2011). The most striking evidence comes from a recent study by Kuhbandner, Rosas-Corona, and Spachtholz (2017) where recognition was not measured with a recollection-dependent ONR as in the aforementioned studies, but with a two-alternative forced choice recognition test (2AFC) that relied on perceptual identification. Importantly, since a 2AFC test does measure memory only more sensitively than an ONR test if participants’ responses are not only based on experiences of recollection or familiarity, participants were encouraged to guess and go with their “gut feelings”; as shown in other research, by encouraging unconsciously informed guessing, the amount of stored information is measured substantially more sensitively than when participants base their memory responses on experiences of recollection and familiarity (Voss & Paller, 2010). When dissimilar perceptual foils were used, memory performance (corrected for guessing) went up to a rate of 47.5%. Even more intriguingly, even when highly similar perceptual foils were used, memory performance was high (22.4%), indicating that high-fidelity representation of unattended stimuli had been stored. Furthermore, even when incidental memory for the unattended stimuli was tested for the first time after 24 hours, memory performance was still far above chance (dissimilar foils: 20.5%, similar foils: 10.9%).

Taken together, the latter studies demonstrate that humans store detailed representations of current sensory stimulations in long-term memory independently of current intentions and the current attentional focus. However, one potential limitation of this astounding ability may be that this holds only for unattended information that is processed in the same sensory processing channel as the attended information. In all of the above mentioned studies, both the attended and unattended information were presented within the same sensory modality (visual) so that it remains to be shown whether detailed long-term memory representations are also formed for unattended information processed in another sensory modality than the attended information. On the one hand, based on findings suggesting that different sensory modalities draw from separate resource reservoirs (e.g., Duncan, Martens, & Ward, 1997; Soto-Faraco & Spence, 2002), one may speculate that unattended information processed in other sensory modalities is stored in long-term memory with similar quality as well. On the other hand, based on findings suggesting that attention increases already the gain of responses from very early processing areas (e.g., Carrasco, 2009; O’Connor, Fukui, Pinsk, & Kastner, 2002), one may speculate that unattended information processed in other sensory modalities is stored in long-term memory with less quality. Preliminary evidence that at least some aspects of the unattended information processed in other sensory modalities is stored in memory comes from a study showing that words that were acoustically presented while participants performed a visual high attentional load task were remembered slightly above chance in a subsequent word recognition test (Sinnett, Costa, & Soto-Faraco, 2006). However, as participants were not instructed to ignore the acoustically presented words, it may still have been the case that attention spilled over to the auditory stream sometimes. Furthermore, as memory was tested only immediately after using a cross-modal recognition test where the words were presented in written form, both the durability and the quality of the stored representations is unknown.

The aim of the present study was to examine whether detailed long-term memory representations are also formed for unattended information processed in another sensory modality than the attended information. To examine this question, participants were simultaneously presented with a rapid stream of visually presented words and an auditory stream of everyday sounds, with the instruction to attend to the words and to press a button every time a word was repeated, and to avoid distraction by the irrelevant sounds as good as possible (for an illustration, see Fig. 1A). No mention was made that their memory for any stimuli would be tested later. Memory for the unattended and incidentally encoded sounds was tested immediately after encoding and after 24 hours. To test memory, a two-alternative forced choice recognition (2AFC) test was used with similar foils belonging to the same basic-level category so that a correct decision required the existence of stored detailed long-term memory representations of the unattended sounds.

Method

Participants

We decided to collect data from at least 41 participants based on the sample size in a similar study (Kuhbandner et al., 2017), and to continue data collection until the end of a semester. In total, 52 undergraduate students participated for course credit. The study was conducted in accordance with APA ethical standards in the treatment of participants; all participants provided written informed consent. One participant was excluded, because he had expected a memory test for the sounds according to the post-experimental questionnaire (see below), resulting in a sample of 51 participants (40 females, $M_{\text{Age}} = 23.00$ years, $SD = 5.40$). All data exclusions, manipulations, and measures in the study are reported.

Materials

The stimulus set consisted of 168 categorically distinct everyday sounds (e.g. the barking of a dog, the humming of a fridge, a starting motor, a glass being filled, a bird singing; sounds were taken from the IADS, Bradley & Lang, 1999, from a freely available online database, or self-created using a recording device; data and information about the stimuli can be downloaded at osf.io/3vgcu). For 72 of the 168 sounds, there was a second exemplar from the same basic-level category; these sound pairs were used in the 2AFC test. The differences between the two sounds of a pair were kept as small as possible while still being distinguishable. The other 96 sounds were filler items. The sound duration varied between one and five seconds, the length of the two sounds of a pair was identical. Volume normalization of the stimuli was performed using an open-source volume normalization software (Mp3Gain) based on the ReplayGain algorithm proposed by Robinson (2001) that estimates the perceived loudness level of a sample and adjusts the sounds to a reference level. This reference level was set to 60dB SPL. The words for the word repetition task were taken from the Berlin Affective Word List (BAWL-R; Vo et al., 2009). In total, 660 neutral, five- to six-letter

German words were used (written in black and uppercase letters, valence from -1 to 1 on a scale from -3 to 3). The words were unrelated to the everyday sounds.

Design and Procedure. The procedure of the experiment was based on the high attentional load paradigm introduced by Rees et al. (1999). Participants were simultaneously presented with a rapid visual stream of words and an auditory stream of everyday sounds (for an illustration, see Fig. 1A). In the visual stream, the words were presented centered on a screen in black on a white background written in bold, capitalized letters in Calibri font at a size of 18 points. Each word was randomly rotated 45° clockwise or counterclockwise and presented for 250 ms, followed by an interstimulus interval of 250 ms. On average once every five words a word was repeatedly shown; there were never two repetitions in a row. On repetition trials, the words were shown in different orientations. In the auditory stream, the sounds were presented to participants via headphones. Each sound was presented only once during this phase of the experiment. In order to exclude primacy and recency effects, the first and last fifteen sounds were filler items only. The remaining 138 sounds (72 target and 66 filler items) were presented in one of four pre-experimentally generated orders that were randomly determined each. The position of target and filler items in the pre-experimentally generated orders was random. The assignment of the exemplars of a sound pair to the incidental study phase was counterbalanced across participants.

Participants were instructed to attend to the visual stream of words and to detect immediate word repetitions by pressing a button, and to ignore the auditory stream of sounds as good as possible. To maximize the focusing of attention on the words and the irrelevance of the sounds, participants were told that the aim of the study was to measure the ability of avoiding distraction by irrelevant sounds. No mention was made that their memory for any of the stimuli would be tested later. Immediately after completing the word repetition task, the participants' memory for half of the sounds was tested in a surprise recognition test. The other half was tested in a second delayed recognition test after 24 hours. The assignment of the sound pairs to the immediate and delayed recognition tests was counterbalanced across participants. In the recognition test, participants consecutively listened to the two sound exemplars of a pair, and they were asked to indicate which of the two sounds had been presented before (2AFC). Participants were told that this task will not be easy as they had ignored the sounds during the previous attentional task, and that they will probably have the feeling of not knowing the answer in many cases. They were also told that numerous previous studies have shown that participants can nevertheless perform remarkably well in such situations when they base their decisions on their intuition. Hence, the participants were asked to follow their “gut feelings” when not knowing an answer. Participants were allowed to proceed at their own pace; if they were not sure about their decision, they could listen to the two sounds of a pair again as often as they wanted. On half of the recognition test trials, the previously presented sound was presented first, on the other half second. Presentation order of the tested sound pairs was random. In the delayed recognition test, after having tested the sounds that had not been tested the day before, the sounds that had been tested the day before were tested again. To ensure that the sounds had been incidentally encoded, after completion of the immediate recognition test, the participants were asked whether they had expected a memory test for the sounds.

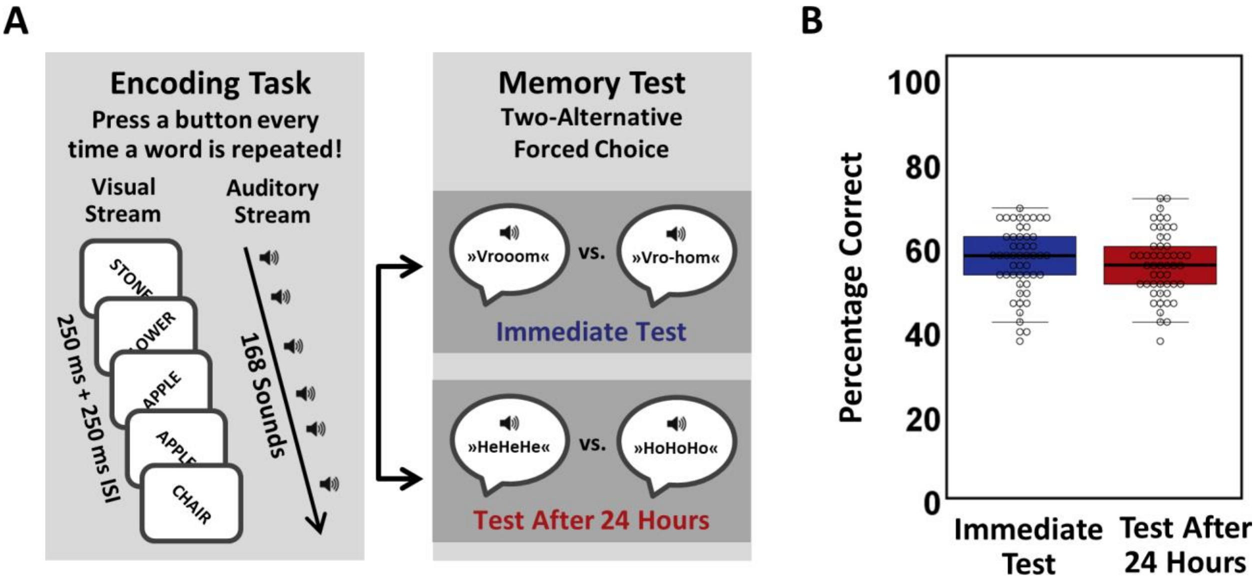

***Figure 1.* Memory paradigm and recognition performance**. The procedure of the experiment is illustrated in (A). In an initial encoding phase, participants were simultaneously presented with a rapid visual stream of words and an auditory stream of everyday sounds. They were asked to attend to the visual stream and to detect immediate word repetitions, avoiding distraction by the irrelevant sounds. No mention was made that memory for any stimuli would be tested later. Memory for half of the sounds was tested in a surprise recognition test immediately afterwards, the other half was tested in a second recognition test after 24 hours. A two-alternative forced choice recognition test was used with foils that were similar to the sounds presented before. Recognition performance is depicted in (B). The box-and-whisker plots show participants’ memory performance (percentage of correct responses) in the immediate memory test and in the memory test after 24 hours. Center horizontal 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.

Results

Word Repetition Task. Participants’ performance in the word repetition task was high (*M* = 70.01%, *SD* = 12.50%, 95% CI [66.58, 73.44]) and in the range of previous studies using the same high attentional load task (e.g., Ruz, Wolmetz, et al., 2005; Ruz, Worden, et al., 2005), indicating that they successfully focused their attention on the words.

Memory Performance. Figure 1B shows the participants' memory performance (percentage of correct responses) in the immediate and the 24-hours delayed recognition tests. In the immediate test, memory performance was far above chance, M = 56.86%, SD = 9.87, 95% CI [54.16, 59.57], $t(50) = 4.97$, $p < .001$, $d = 0.70$. In the 24-hours delayed test, memory performance for sounds that were tested for the first time was still far above chance, M = 55.83%, SD = 9.58, 95% CI [53.20, 58.46], $t(50) = 4.35$, $p < .001$, $d = 0.61$. There was no significant forgetting observed across the delay of 24 hours, $M_{Difference}$ = 1.03%, SD = 11.81, 95% CI [-2.21, 4.27], $t(50) = 0.63$, $p = .534$, $d = 0.09$. Memory performance in the delayed test for sounds that had already been tested in the immediate test was above chance as well, M = 54.19%, SD = 6.39, 95% CI [52.44, 55.95], $t(50) = 4.69$, $p < .001$, $d = 0.66$. Performance did not significantly differ between sounds that were tested for the first time after 24 hours and sounds that had already been tested in the immediate test, $M_{Difference}$ = 1.63%, SD = 11.51, 95% CI [-1.52, 4.79], $t(50) = 1.01$, $p = .316$, $d = 0.14$.

Additionally, we also calculated a sensitivity index d'_{FC} corrected for response bias (for details, see Wickens, 2002, p. 101). The sensitivity index corrected for bias differed significantly from zero for both the immediate test, $d'_{\mathrm{FC}} = 0.36$, SD = 0.53, 95% CI [0.21, 0.50], $t(50) = 4.84$, $p < .001$, $d = 0.68$, and the 24-hours delayed test, $d'_{\mathrm{FC}} = 0.31$, SD = 0.51, 95% CI [0.17, 0.45], $t(50) = 4.38$, $p < .001$, $d = 0.61$. There was no significant decrease of d'_{FC} across the delay of 24 hours, $d'_{FC\text{-}Difference} = 0.04$, SD = 0.63, 95% CI [-0.13, 0.22], $t(50) = 0.51$, $p = .612$, $d = 0.07$. Memory performance in the delayed test for sounds that had already been tested in the immediate test was above chance as well, $d'_{\mathrm{FC}} = 0.23$, SD = 0.35, 95% CI [0.13, 0.32], $t(50) = 4.73$, $p < .001$, $d = 0.66$. The sensitivity index did not significantly differ between sounds that were tested for the first time after 24 hours and sounds that had already been tested in the immediate test, $d'_{FC\text{-}Difference} = 0.09$, SD = 0.62, 95% CI [-0.09, 0.26], $t(50) = 0.99$, $p = .329$, $d = 0.14$.

To address the possibility that the observed memory performance for the sounds might be attributable to a covert allocating of attention to the sounds during encoding, a number of additional analyses were performed (see Figure 2).

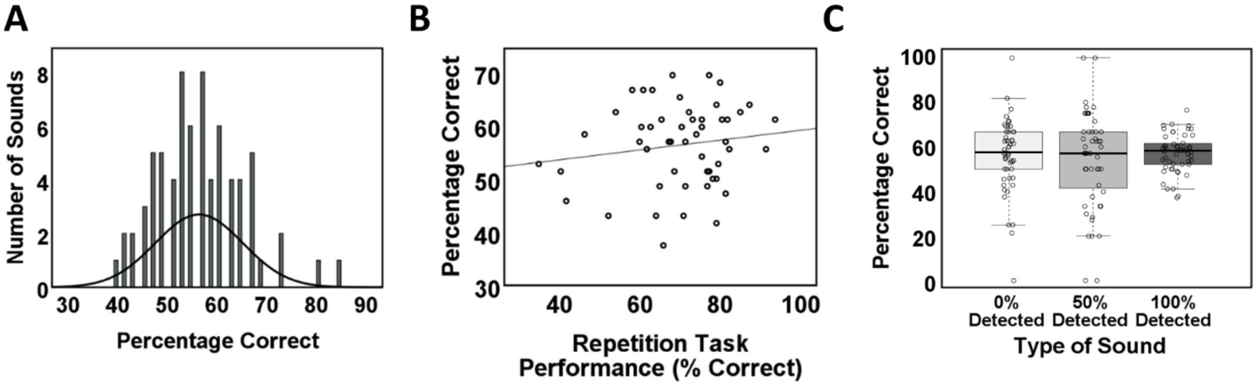

***Figure 2*. Results of the Additional Analyses.** The distribution of the percentage of correct responses across the 72 sound pairs is depicted in (A). The relation between the participants' performance in the word repetition task and the average percentage correct is depicted in (B). The box-and-whisker plots depicted in (C) show participants' memory performance for sounds during whose presentation no word repetitions were detected (11.1% of sounds), 50% of the word repetitions were detected (24.9% of sounds), and all word repetitions were detected (64.1% of sounds). Center horizontal 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 percentage of correct responses was collapsed across the immediate test and the delayed test for sounds tested for the first time.

To rule out that the observed memory performance was driven only by a few specific sounds that may automatically have attracted attention, we determined the average percentage correct for each sound pair across participants (collapsed across the immediate test and the delayed test for sounds tested for the first time; this was done for all of the following analyses). As shown in Figure 2A, performance was normally distributed across the sounds, $W(72) = 0.973$ $p = .125$. To rule out that the observed memory performance was driven by a transient shift of attention away from the visual stream of words during encoding, two further analyses were performed. First, we correlated the participants' performance in the word repetition task with their later memory performance. If the observed memory performance is attributable to a switching of attention away from the word repetition task, a negative correlation should be observed. However, performance in the word repetition task and memory performance were not significantly correlated, $r = .15$, $p = .296$ (see Figure 2B). Second, we compared memory performance for sounds during whose presentation all word repetitions were detected (64.1% of the target sounds), only 50% of the word repetitions were detected (24.9% of the target sounds), and no word repetitions were detected (11.1% of the target sounds). Memory performance did not differ between the three types of sounds ($M_{\text{All Detected}}$ = 57.15%, *SD* = 8.66, 95% CI [54.77, 59.53]; $M_{\text{50\% Detected}}$ = 54.67%, *SD* = 21.72, 95% CI

[48.71, 60.63]; $M_{0\%\ \text{Detected}}$ = 56.25%, *SD* = 16.30, 95% CI [51.78, 60.72]), $F(2,100) = 0.355$, $p = .702$, $\eta^2_p = 0.007$ (see Figure 2C).

Discussion

At any moment, a myriad of information reaches our senses, of which only a small fraction is attentively processed. Early on, it has been suggested that the unattended information is only weakly processed and partially analyzed, leaving no recognizable trace in memory (Broadbent, 1958), an assumption that is still believed to be true at least if the demands of the attended task are high and the unattended information is irrelevant for one's current goals (Lavie, 2010), supported by numerous studies (e.g., Lavie et al. 2009; Rees et al., 1999; Ruz, Wolmetz, et al., 2005; Ruz, Worden, et al., 2005). By using a more sensitive recognition test (2AFC test) than in the previous studies (ONR test), the present results challenge this assumption. Participants were able to recognize unattended and irrelevant auditory information that was incidentally encoded in a visual high attentional load task, even though a correct response required detailed knowledge about the auditory information, and even when memory was tested for the first time after a delay of 24 hours, without significant forgetting across time. These results corroborate previous findings in the visual domain (Butler & Klein, 2009; Kuhbandner et al., 2017) and extend them by showing that detailed and durable long-term memory representations are even formed for unattended information processed in a different sensory modality than the attended information.

Together with the findings of Butler and Klein (2009) and Kuhbandner et al. (2017), the present study provides clear evidence that humans store detailed copies of current sensory stimulations in long-term memory, independently of current intentions and the current attentional focus. In fact, based on findings in the domain of implicit memory, showing that past perceptual experiences can influence behavior without conscious awareness even after only a single observation and longer retention intervals (e.g., Musen & Treisman, 1990; Mitchell & Brown, 1988; Mitchell, 2006), it has been postulated that there is a perceptual representation memory system that operates independently of the episodic memory system (Schacter, 1990; for a similar account see Johnson, 1983). However, the operating characteristics and representational format of such a potentially existing memory system have remained relatively unclear to date (e.g., Butler & Berry, 2001). Regarding operating characteristics, the present results indicate that the perceptual representation memory system operates independently of one's current attentional focus and intentions. Regarding the representational format, the present results suggest that perceptual experiences are stored in detail.

In particular, since it is commonly assumed that attention is required for the binding of features into coherent object representations (e.g., Treisman & Gelade, 1980), it seems that the unattended information is stored in the form of independent feature representations. Indeed, such an assumption is supported by previous findings showing that low-level feature information can be retained with high precision in long-term memory (e.g., Magnussen & Dyrnes, 1994), and that the quality of object representations in perceptual long-term memory can be predicted from early preattentive brain activities (Spachtholz & Kuhbandner, 2017). In line with that and as far as the processing of auditory stimuli is concerned in particular, it has been demonstrated that participants are able to remember specific spectro-temporal peculiarities in noise stimuli (i.e., to remember specific, fine-grained features of the presented stimuli; Agus & Pressnitzer, 2013; Agus, Thorpe, & Pressnitzer, 2010).

In the present study, similar pairs of sounds were used. As in numerous previous studies (e.g. Brady, Konkle, Alvarez, & Oliva, 2008; Hutmacher & Kuhbandner, 2018), similarity was defined as semantic similarity, that is, sounds were considered as similar when they belonged to the same basic-level category. For instance, participants had to differentiate between the humming sounds of two different fridges or the sound of filling two different glasses with water. From the perspective of memory, the consequence is that remembering a sound at the level of semantics was insufficient for a correct response. Rather, to reach a correct response, perceptual information about the initially presented sounds had to be stored and retrieved. Beyond semantics, the similarity of sounds can also be defined on the sensory-perceptual level. However, previous research has shown that determining the sensory-perceptual similarity of everyday environmental sounds is non-trivial for several reasons. First, everyday environmental sounds differ along many more dimensions than simple laboratory-generated stimuli so that defining similarity for this kind of sounds becomes vastly more difficult (see e.g. Dickerson & Gaston, 2014). Second, complex auditory stimuli such as everyday environmental sounds seem to be more than simple linear combinations of single discrete properties. For instance, simply varying the position of a tone in a sequence or adding a tone to the sequence affects discrimination performance dramatically, although the changes are quite small from a quantitative perspective (Watson, Wroton, Kelly, & Benbassat, 1975). This means that even if all different stimulus dimensions can be quantified, it is difficult to see how these different dimensions could be integrated into a single similarity score that can be related to the participants' perception (e.g., Susini, Lemaitre, & McAdams, 2012). Hence, we decided to make the pairs of the used everyday environmental sounds perceptually similar only by controlling for object-unrelated features such as length and volume of the sounds. Nevertheless, systematically exploring the influence of similarity at the sensory-perceptual level using optimized acoustic stimuli seems to be a promising topic for future research.

In view of the percentages of correct responses observed in the immediate test (56.86%) and the 24-hours delayed memory test (55.83%), at first glance, the overall memory effect seems rather small given a guessing probability of 50%. However, first, it is important to note that the percentage of presented objects that were stored so that they were successfully discriminated from the foil objects in the test is not simply the difference between the observed percentage of correct responses and the guessing probability, but two times the difference (e.g., Brady, Konkle, Alvarez, & Oliva, 2013). Second, one has to take into account, that similar foils were used in the memory tests so that a correct response required that detailed memory representations were stored. Research in the visual domain has shown that performance is much better when less similar foils are used (Kuhbandner et al., 2017), suggesting that representations of many more objects are stored but partly in less quality. Third, in view of previous studies that have used old-new recognition tests, suggesting that memory for attended sounds is relatively poor (Cohen, Horowitz, & Wolfe, 2009) and memory for unattended stimuli generally absent (e.g., Lavie et al., 2009; Rees et al., 1999; Ruz, Wolmetz, et al., 2005; Ruz, Worden, et al., 2005), the finding that memory is significantly above chance when measured with a two-alternative forced choice test seems relatively surprising.

In view of recent findings in the domain of visual memory, showing that observers can successfully recognize details of thousands of visual images after having studied them only for a few seconds each (e.g., Brady, Konkle, Alvarez, & Oliva, 2008), it has been conjectured that existing cognitive and neural models of long-term memory storage and retrieval are challenged given the large amount of stored information (Brady et al., 2008). The finding that detailed representations are even formed for a significant fraction of the incoming unattended, irrelevant, and incidentally encoded information suggests that this challenge may even be larger than initially believed.

Context of the Research

We are fascinated by the question of how many of the thousands of perceptual experiences we make every day are stored in long-term memory. Whereas earlier studies demonstrating phenomena such as change blindness (Simons & Rensink, 2005) or inattentional amnesia

(Wolfe, 1999) seemed to support the idea that long-term memory representations for perceptual experiences are rather sparse, more recent studies have shown that in fact detailed memory representations are stored. This does not only hold true for visual information (e.g., Brady et al., 2008; Kuhbandner et al., 2017), but also for haptic (Hutmacher & Kuhbandner, 2018), and – as demonstrated in the present study – for auditory information. Building on these results, in future research, we want to explore the nature of these detailed memory representations. Preliminary evidence suggests that there are at least two options: storing information as independent features or as bound objects (e.g., Spachtholz & Kuhbandner, 2017). Furthermore, we are also interested in investigating potential selection mechanisms. Apparently, not all incoming information is stored in long-term memory so that it is important to unravel the mechanisms by which the perceptual long-term memory system separates important from unimportant information (e.g., Seitz, Kim, & Watanabe, 2009; Swallow & Jiang, 2010).

2.3 Study 3 – Why Is There So Much More Research on Vision Than on Any Other Sensory Modality?

This is a pre-copy-editing, author-produced version of an article published 2019 in Frontiers in Psychology following peer review. The official citation that should be used in referencing this material is Hutmacher, F. (2019). Why Is There So Much More Research on Vision Than on Any Other Sensory Modality? *Frontiers in Psychology, 10,* 2246. doi:10.3389/fpsyg.2019.02246

Abstract

Why is there so much more research on vision than on any other sensory modality? There is a seemingly easy answer to this question: It is because vision is our most important and most complex sense. Although there are arguments in favor of this explanation, it can be challenged in two ways: by showing that the arguments regarding the importance and complexity of vision are debatable and by demonstrating that there are other aspects that need to be taken into account. Here, I argue that the explanation is debatable, as there are various ways of defining “importance” and “complexity” and, as considering these different definitions proves, there is no clear consensus that vision is indeed the most important and most complex of our senses. Hence, I propose two additional explanations: According to the methodological-structural explanation, there is more research on vision because the available, present-day technology is better suited for studying vision than for studying other modalities – an advantage which most likely is the result of an initial bias towards vision, which reinforces itself. Possible reasons for such an initial bias are discussed. The cultural explanation emphasizes that the dominance of the visual is not an unchangeable constant, but rather the result of the way our societies are designed and thus heavily influenced by human decision-making. As it turns out, there is no universal hierarchy of the senses, but great historical and cross-cultural variation. Realizing that the dominance of the visual is socially and culturally reinforced and not simply a law of nature, gives us the opportunity to take a step back and to think about the kind of sensory environments we want to create and about the kinds of theories that need to be developed in research.

Keywords: visual dominance, visuo-centrism, visual turn, social constructionism, history of the senses, multimodal integration, perception

Why Is There So Much More Research on Vision Than on Any Other Sensory Modality?

It has already been observed, about a hundred years ago, that research on perception and perceptual memory often in fact is research on visual perception and visual memory, while other sensory modalities play a minor role (Katz, 1925/1989). Gallace and Spence (2009) supported this observation with empirical data. When searching the PsycINFO database for studies containing “visual”, “auditory”, “gustatory”, “olfactory” or “tactile/haptic memory” in the title, they found two interesting results. First, there were more studies on visual memory than studies on the memory of all other sensory modalities combined. Second, while there were still a considerable number of studies on auditory memory, research on olfactory, gustatory, and haptic memory was even more limited. I repeated the same search for this paper (see Fig. 1A). As Gallace and Spence (2009) conducted their search more than ten years ago, I also added the data for the past decade (see Fig. 1B; note that an updated version of the graph containing data until the end of 2010 is presented by the authors themselves in Gallace & Spence, 2014, p. 112). The pattern has remained the same. If anything, the proportion of studies on visual memory has increased (from 68.04% among the studies conducted until 2007 to 77.46% among the studies conducted since the beginning of 2008).[1]

The question is: Why? Why is there so much more research on vision than on any other sensory modality? There is a seemingly easy answer to this question, which I will call the “textbook explanation”: Vision is our most important and most complex sensory modality and this is mirrored in the number of studies. Although there are indeed arguments in favor of the textbook explanation, I will show that this answer alone is too simplistic for at least two reasons. First, the textbook explanation is debatable insofar as the notion that vision is our most important and most complex sensory modality depends on the definition of “importance” and “complexity”. Second, the textbook explanation is incomplete as there are further explanations to be considered: (a) the idea that the dominance of the visual has methodological-structural reasons, and (b) the observation that the importance ascribed to the different sensory modalities varies across times and cultures. Hence, the impression that vision is our most important sensory modality flows partially, at least, from the fact that contemporary Western societies are visual societies and that researchers from these countries still dominate the scientific discourse in psychology.

The Textbook Explanation

If you open a textbook on perception or cognitive psychology, you will realize that normally more chapters are dedicated to vision than to any other modality (e.g. Goldstein, 2010; Kandel, Schwartz, & Jessel, 2000; Sternberg & Sternberg, 2017). Apparently, this decision seems self-evident to the authors and is thus often either not explained at all or explained only briefly. Sternberg and Sternberg (2017) simply state, for instance, that “vision is the most widely recognized and the most widely studied perceptual modality” (p. 72) while Kandel et al. (2000) claim that “[m]ost of our impressions about the world and our memories of it are based on sight” (p. 492). In the same spirit, Gerrig and Zimbardo (2008) write that “[v]ision it the most complex, highly developed, and important sense for humans and most other mobile creatures” (p. 103). A more detailed explanation of this idea can be found in a chapter on perception by Pike, Edgar, and Edgar (2012):

> [That there has been far more research on vision] is because when we interact with the world we rely more on vision than on our other senses. As a result, far more of the primate brain is engaged in processing visual information than in processing information from any of the other senses. (p. 67)

The last two quotes contain the two elements of what I will call the “textbook explanation”. According to the textbook explanation, there is so much research on vision compared to research on the other modalities (1) because vision is more *important* than other modalities for our daily experience as well as the way we interact with the world and (2) because the processing of visual information is far more *complex* and occupies larger parts of our brain than the processing of sensory information from other modalities.

In fact, a wide range of evidence supports these two claims. As far as the *importance* of vision is concerned, two kinds of importance have to be distinguished: the *subjective* importance, that is the importance of a certain sensory modality from a first-person perspective, and the *empirical* importance, that is the importance of a certain sensory modality when it comes to processing and remembering information as well as navigating through the world. Let us examine both and let us begin with the subjective importance.

When asked to rate the extent to which different modalities are part of the experience with objects, most people put vision first (Schifferstein, 2006; Schifferstein, Otten, Thoolen, & Hekkert, 2010; Tranel, Logan, Frank, & Damasio, 1997). Although these studies indicate that vision is indeed the most important modality for most people from a subjective point of view, one can address this question even more directly: Imagine losing one of your sensory modalities. Losing which modality does scare you the most? I conducted a survey asking exactly this question (N = 91, 63 females, 27 males, 1 diverse, age 19-62 years, M_{age} = 29.44, SD_{age} = 10.96). For the overwhelming majority of people the answer is *vision* (73.63%). The pattern across the different modalities (see Fig. 2) is similar to the pattern for the number of studies conducted in each sensory modality (see above, Fig. 1). This similarity suggests a straightforward answer to the question as to why there is so much more research on vision than on any other sensory modality: People tend to investigate those modalities that are most important to them. Interestingly, the subjective dominance of the visual is also reflected in language. As demonstrated by Winter, Perlman, and Majid (2018), there is a higher frequency of visual words and a greater number of unique visual words compared to words for other sensory modalities in a wide range of English corpora. As it has been argued that the vocabulary of a language is optimized for satisfying the communicative needs of their speakers (for a discussion of this idea in the context of colors see e.g. Berlin & Kay, 1969; Cook, Kay, & Regier, 2005), these results seem to mirror the subjective importance of the visual.

The idea that vision is indeed the most important modality is supported by numerous studies demonstrating *visual dominance* (for a meta-analysis see Hirst, Cragg, & Allen, 2018; for a recent philosophical account see Stokes & Biggs, 2014). The term “visual dominance” refers to the observation that information from different senses is not treated equally. Rather, the processing of visual information seems to dominate the processing of information from other modalities. The reasons for this are still debated. While some argue that visual dominance flows from the fact that vision is more accurate and reliable than the other senses, others argue that the opposite is true and that people have to focus on visual input, because of its rather weak capacity to alert the organism to its occurrence (see Posner, Nissen, & Klein, 1976, for the classic and Spence, Shore, & Klein, 2001, for an updated elaboration of the latter view). One famous example of visual dominance is the so-called “Colavita effect” (Colavita, 1974; Colavita, Tomko, & Weisberg, 1976; for a recent review see Spence, Parise, & Chen, 2012). When a visual and an auditory stimulus are presented simultaneously, participants show a strong tendency to respond to the visual stimulus. Even more, participants frequently report not having perceived the auditory stimulus at all. The finding of visual dominance over auditory stimuli has also been extended to visual dominance over haptic stimuli (Hecht & Reiner, 2009; for earlier attempts see Rock & Harris, 1967; Rock & Victor, 1964).

Hence, evaluating both the subjective as well as the empirical importance of the different sensory modalities seems to lead to the conclusion that vision is more important than the other modalities. However, what about complexity? The core idea of the complexity argument is simple: A large part of the human – or more generally speaking: primate – neocortex is involved in processing visual information, while information from other sensory modalities is processed in far smaller brain regions. When investigating the macaque neocortex, for instance, it turned out that 54% of the macaque neocortex are involved in visual processing (Van Essen, Felleman, DeYoe, Olavarria, & Knierim, 1990). In contrast, only a small fraction of the neocortex is exclusively dedicated to auditory (3%) or somatosensory processing (11%). To this, it can be added that the estimated number of sensors and afferents as well as the information transmission rate is higher for vision than for any other sensory modality (see Zimmerman, 1989). Thus, one may argue that the greater "brain power" available for processing visual information allows for a more fine-grained analysis of the incoming visual stimulation compared to the stimulation from other modalities.

Questioning the Textbook Explanation

The textbook explanation can be challenged in two ways: by showing that the arguments regarding the importance and complexity of vision are debatable and by demonstrating that the textbook explanation is *incomplete* as there are other aspects that need to be considered.

Why the Textbook Explanation Is Debatable: Importance

At first glance, it appears obvious why the vast majority of participants, in the survey reported above, stated that they are most afraid of losing their visual abilities. Just imagine for one moment, how vital vision is for most of your daily activities, ranging from hobbies (e.g. reading, watching a movie, playing tennis) and daily routines (e.g. grocery shopping, going by car or bike, cleaning your apartment) to your work environment (e.g. writing mails, working on your computer, administering any kind of machine). However, our present-day societies offer a wide range of support to blind people so that they can remain active members of their community. Although losing sight may be perceived as a traumatic event and although it profoundly changes the way one interacts with the world, it does normally not endanger the survival of the individual – and probably not even its social integration.

Now imagine – for comparison – losing your haptic abilities: You would not feel anything when hugging your loved ones or when caressing their faces; you could not tell whether your back hurts or whether you are comfortably seated; you would not notice when stepping barefoot on a piece of broken glass (unless you see the blood coming from you wound), and so on. In short, you would be deprived of some of the most important and most intimate aspects that come with the fact that human beings are physical beings that are –

literally – *in touch with the world*, not to forget that losing the sense of touch would drastically diminish the ability to detect dangers for the physical integrity. In this context, it is interesting to consider congenital insensitivity to pain, a very rare condition in which people are – as the name already suggests – insensitive to pain from birth onwards (for a review see Nagasako, Oaklander, & Dworkin, 2001). Although these people have no cognitive defects, they often die in childhood and generally have a decreased life expectancy. It is easy to see why:

> [These people are not] able to determine if a bone is broken or if they have bitten off the tip of their tongue unless they see the swelling of the surrounding tissue or taste blood in their mouth. Because of this inability to sense pain, it is common for patients with congenital insensitivity to pain to have unseen infections as well as have a multitude of bruises, wounds, and broken bones over their lifetime. (Hellier, 2016, p. 118)

Thus, it seems that – at least in our present-day societies – haptic abilities such as the ability to sense pain are more important *for our survival* than visual abilities. In line with this, it has also been hypothesized that physical contact is a necessary precondition for the healthy development of the individual. Skin-to-skin contact between the mother and the infant in the first hour after birth has vital advantages for short- and long-term health (Klaus, Jerauld, Kreger, McAlpine, Steffa, & Kennell, 1972; for a recent review see Widström, Brimdyr, Svensson, Cadwell, & Nissen, 2019). As this effect may rather be due to the formation of an emotional bond which is facilitated through skin-to-skin contact rather than due to the skin-to-skin contact *per se*, it is interesting to consider another developmental issue: At birth, our visual system is severely underdeveloped. Hence, in the first months of their lives, newborns need to learn to make sense of the incoming visual information. As the sense of touch already plays a crucial role for the unborn child, it seems legitimate so speculate that newborns use their well-developed sense of touch to achieve this (see Grunwald, 2017; Martin, 1992). In fact, it has been demonstrated that newborns can extract the shape of an object by haptically exploring it and that they can transfer this knowledge so that they are able to visually recognize the same object they had only touched before (Sann & Streri, 2007; Streri & Gentaz, 2003; 2004). In addition, remember that many of the newborn reflexes such as the grasp or suck reflex are shown as a response to being touched. From this perspective, one may argue that our sense of touch is more important than our sense of vision as the former plays an essential role in the development of the latter (see e.g. Gottlieb, 1971, for an ontogenetic account of sensory function). In particular, it has been argued that "early tactile experiences

[…] might strongly contribute to shaping and characterizing the emotional, relational, cognitive, and neural functioning of the adult individual" (Gallace & Spence, 2014, p. 178).

Note, that these remarks about the importance of haptics are not meant to establish a haptic-centered version of the textbook explanation claiming that haptics should be treated as the most important sensory modality. Rather, I have tried to show that it is far more difficult to decide which sensory modality is most important for human beings than one may at first think. In fact, it is a matter of perspective; it is a matter of the aspects taken into consideration (for an example of differences between people see Delwiche, 2003). Interestingly, the reported differences between vision and haptics may be the result of the fact that vision is a *distant sense* while touch is a *proximal sense* (for this distinction see e.g. Katz, 1925/1989; Klatzky & Lederman, 2011; Rodaway, 1994; Trope & Liberman, 2010).[2] Expressed in plain words, touch gives us information about the way our body is embedded in the environment. Touch is an integral part of the existential experience of being a physical creature (see e.g. O'Shaughnessy, 1989). At the same time, we are consciously unaware of most of our haptic sensations: You can direct your attention towards your feet in order to find out how they feel in your shoes right now. If you are not intentionally directing your attention towards your haptic sensations, however, you will not notice them most of the time (until someone taps you on your shoulder or you take a hot shower on a cold winter day). Compare this to vision: As long as you are awake, it is hard to prevent the visual impressions and changes in your environment from entering your consciousness – no matter how relevant or irrelevant this information may be for your current goals.[3] That is because vision as a distant sense informs us about the surroundings; it informs us *about the world*. Thus, vision is especially important when it comes to actively exploring and navigating in this world:

> A view comprehends many things juxtaposed, as co-existent parts of one field of vision. It does so in an instant: as in a flash one glance, an opening of the eyes, discloses a world of co-present qualities spread out in space, ranged in depth, continuing into indefinite distance […]. (Jonas, 1954, p. 507)

Put differently, vision as a distant sense has a *qualitatively* different function than touch as a proximal sense. This qualitative difference renders conclusions about the absolute importance of a given sensory modality almost impossible. In this context, one may additionally consider olfaction: "Often, we rely on our sense of smell in order to decide whether or not it is safe to engage further with a given stimulus" (Gallace, Ngo, Sulaitis, & Spence, 2012, p. 16). Thus, although smell may play a rather minor role in everyday life, it becomes extremely important in potentially harmful or even life-threatening situations, such as determining whether some food is rotten, detecting a gas leak or smelling fire.

In short, the degree to which vision dominates the research on the different sensory modalities cannot simply be explained by claiming that vision is the most important modality. As it will turn out in the next section, the same applies to the complexity argument.

Why the Textbook Explanation Is Debatable: Complexity

The complexity argument was based on the assumption that a large part of the human brain is specialized on visual processing while relatively small parts are specialized on processing information from other sensory modalitities. This assumption has been questioned in recent years: Instead of regarding the senses as strictly separated entities, it has become quite common to accept that they often interact and influence each other, which is also mirrored in the neural underpinnings (for reviews see e.g. Alais, Newell, & Mamassian, 2010; Ghazanfar & Schroeder, 2006). It has even been argued that the multisensory nature of the neocortex may force us "to abandon the notion that the senses ever operate independently during real-world cognition" (Ghazanfar & Schroeder, 2006, p. 278). Interestingly, multisensory integration does not only occur in the later brain regions in the temporal and frontal cortices, but also in earlier brain regions and even in the primary sensory cortices. Moreover, brain regions previously believed to be visual by nature are used during Braille reading (e.g. Sadato, Pascual-Leone, Grafman, Ibañez, Deiber, Dold, & Hallett, 1996; Büchel, Price, Frackowiak, & Friston, 1998) and for processing auditory information (e.g. Burton, Snyder, Conturo, Akbudak, Ollinger, & Raichle, 2002; Röder, Stock, Bien, Neville, & Rösler 2002) in blind people. As multisensory processing appears to be the rule rather than the exception, claiming that a large part of the human brain is exclusively specialized for processing visual information seems at least debatable (see e.g. Shimojo & Shams, 2001) – or as Lacey and Sathian (2008) put it: "The crossmodal activity of visual cortex likely reflects modality-independent representations of objects and other stimuli such as motion […]. Such findings increase support for the idea of a 'metamodal' brain organized around task processing rather than separate sensory streams" (p. 257).

However, this line of reasoning is not the only way to question the complexity argument: Why should the size of brain regions specialized on processing information from a certain modality be the only criterion at all, when it comes to determining complexity? One could also take into account the number of different receptor cells, for instance: While humans have only two major classes of photoreceptor cells (rods and three kinds of cones), they possess several hundred different kinds of olfactory receptor cells (Axel, 1995; Glusman, Yanai, Rubin, & Lancet, 2001) and can discriminate more than one trillion olfactory stimuli (Bushdid, Magnasco, Vosshall, & Keller, 2014). Alternatively, remember that the skin is the largest sensory organ of the human body, accounting for more than a tenth of total body weight (Field, 2001; Martini & Nath, 2009; Montagu, 1971). Again, these examples are not meant to claim that vision is *definitely not* the most complex modality, but rather that there are various ways of defining complexity (for an attempt to distinguish different meanings of complexity in the chemical senses see Spence & Wang, 2018). Moreover, no definition presented here seems to provide clear evidence that vision is beyond any doubt the most complex sensory modality. As both the importance and complexity argument are insufficient for explaining the degree to which vision dominates the research on the different sensory modalities, it seems necessary to look for other possible explanations.

Alternative Explanations

Here, I present and discuss two additional explanations which can help illuminating the bias towards vision in research. The methodological-structural explanation claims that research on vision is often easier than research on other modalities and that this the result of an initial bias towards vision that reinforces itself; the cultural explanation carves out that the dominance of the visual is not a historical constant, but rather a result of the way (Western) societies are designed.

The Methodological-Structural Explanation

Imagine having to set up an experiment that investigates long-term memory for everyday objects. If you decided to present the objects *visually* on a computer screen, your task would be straightforward: Use your favorite search engine and collect as many images of as many different objects as possible. Instead, you may also refer to one of the publicly available databases, offering thousands and thousands of images (see e.g. Brady, Konkle, Alvarez, & Oliva, 2008; Konkle, Brady, Alvarez, & Oliva, 2010). If you decided to present the objects *haptically*, your task would be much harder: Even if you had a list containing the names of all objects used in a previous study as well as photos of these objects (e.g. Hutmacher & Kuhbandner, 2018), this would be of limited use for your own study, as it would not free you from the necessity to buy and collect all the objects on your own. And the struggle continues: The objects gathered for haptic presentation will occupy much more space than the images of objects stored on your hard drive. Even setting up the actual experiment is easier when working with images presented on a computer screen, as with all programs designed for creating experiments, many potential methodological flaws are easy to avoid. The duration of the stimulus presentation can be determined precisely, counterbalancing within and between participants is normally achieved with a couple of mouse clicks (or lines of code), and the responses of the participants are automatically recorded and coded as correct or false. All these things become vastly more difficult when doing the same experiment involving haptic exploration, as the experimenter has to navigate carefully between the objects (a wine glass *is* fragile, the image of a wine glass is not), keep track of the objects that were already presented, make sure that the participants do not explore the objects too long, and so on.

In short, while there is a lot of off-the-shelf technology available for studying vision, this is not the case for other sensory modalities such as touch (see e.g. Krueger 1989, p. 2, reporting personal communication from Lederman). However, this conclusion is not the end of the methodological-structural explanation. Instead, one could ask further: What could be the reason that the available technology is better suited for studying vision than the other modalities? There are two possible answers to this question.

First, one may argue that vision is *by nature* easier or that the other senses are *by nature* harder to investigate. Maybe vision has a subtle advantage as it “is the ideal distance-sense” (Jonas, 1954, p. 517), that is, as it does not only *allow for distance* to the stimulus (light travels farther than sound or smell), but *gains by distance* as “the best view is by no means the closest view” (p. 518) – a feature, which is perfectly suited for the distanced and objective perspective of an experimenter (see Classen, 1993). In contrast, it seems hard to imagine how there could be off-the shelf technology for studying the chemical senses, for instance: Although researchers have tried to, no one has yet found a digital way of stimulating the chemical senses, which would be an important precondition for setting up standardized and easily controllable experiments (see Spence, Obrist, Velasco, & Ranasinghe, 2017). The same can be said about haptic long-term memory: Whoever wants to study the haptic exploration of everyday objects will have to collect the respective objects. There seems to be no way around this.

Even if there is a way around this in some cases, however, the tools developed to study other senses such as touch (see e.g. Grunwald, Ettrich, Busse, Assmann, Dähne, & Gertz, 2002; Mueller, Winkelmann, Krause, & Grunwald, 2014), are not widely spread and were constructed by the authors in a laborious process in order to test their hypotheses (see Grunwald, 2017). Rather than demonstrating that present-day technology used to investigate haptics is equal to the technology to investigate vision, these efforts to create adequate instruments in the absence of an established technology remind of the situation at the end of the 19th century, when the first experimental psychological laboratories were founded (see e.g. Caudle, 1983; Schoenherr, 2017). At that time, creating tools for research on vision was a laborious process. Hence, one can get the impression that the development of haptic technology lags behind in time.

This observation leads to the second answer to the question as to why the available technology is better suited for studying vision than the other modalities: The "Matthew effect" (Merton, 1968) describes the fact that the networks of science are designed in a way that creates more attention for (and allocates more rewards to) already well-known researchers and well-established research topics while rather unknown fields and scientists remain largely unnoticed. Thus, one could hypothesize that instead of (or at least in addition to) being naturally better suited for investigation, vision may have had an arbitrary advantage in the beginning of experimental research and that this initial advantage has perpetuated and possibly even reinforced itself since then. Classen, Howes, and Synnott (1994) confirm the idea of a Matthew effect in the research on different modalities by comparing the status of vision to the status of smell: "While the high status of sight in the West makes it possible for studies on vision and visuality […] to be taken seriously, any attempt to examine smell runs the risk of being brushed off as frivolous and irrelevant" (p. 5). Expressed differently, funding for research into vision might be much easier to obtain than funding for smell or touch. This might in turn bias researches towards doing research on vision as it is easier to get funding, and so on.

There are various possible reasons why the study of vision may have had an advantage in the beginning of experimental research: (1) researchers at the time may have had personal reasons to study vision instead of other modalities (e.g. because they had the subjective impression that vision is their most important modality); (2) researchers may have been biased towards vision due to a long history of visual dominance in Western societies (see the next section); (3) apparently, "early psychologists enthusiastically borrowed and adapted the scientific instruments that had heretofore been used to explore problems related to the physical laws of acoustics and optics and the physiology of the sense organs" (Caudle, 1983, p. 20-21), almost automatically leading to research focusing on vision and hearing;[4] (4) vision may have a special appeal to scientists as it appears more objective to modern scientists following empiricist traditions than the other senses (see above): "The detachment of sight, distancing spectator from spectacle, makes the cherished objectivity of the scientist possible" (Classen, 1993, p 6).

In conclusion, the methodological-structural explanation claims that there is more research on vision because the available, present-day technology is better suited for studying vision than for studying other modalities. Although one may claim that vision is easier to investigate by nature, it seems quite likely that this claim and thus the technological advantage for vision is at least partially the result of a Matthew effect: As there is more research on and easier accessible technology for vision compared to other modalities today, there will most likely be more research on and technology for vision tomorrow. In addition to the self-perpetuating process proposed by the Matthew effect, there may also be a cultural explanation for the bias towards vision.

The Cultural Explanation

At first sight, one may think of visual dominance as a cultural constant that can be traced back to antiquity (for a history of the senses see e.g. Classen, 1993; Jütte, 2005). When Plato writes about the senses, for instance, he puts the greatest emphasis on vision, which he even describes as "divine" in one place (see Jütte, 2005, p. 35). Generally speaking, he favors the supposedly more rational "higher senses" vision and audition over the other "lower senses", which he believed to be more subjective and bound to bodily reactions (see e.g. Schellekens, 2009). In a similar manner, Aristotle creates a ranking of the senses, putting vision first, followed by hearing, smell, taste, and touch. Although subsequent philosophers did not agree with the classical Aristotelian hierarchy in every respect, vision is almost always ranked as the highest sense in Western societies throughout the medieval ages up until today. In this context, it is especially interesting that the study on the frequency of words referring to the different sensory modalities quoted above, did not only find an overall higher frequency of visual words in the investigated English corpora. When looking at the average frequencies for each modality based on the ten most exclusive words per modality, there was hardly any change in the past 200 years (see Winter et al., 2018, Fig. 5), suggesting that the hierarchy of the senses remained unchanged.

Although the Aristotelian hierarchy has undeniably had a huge influence on the conceptualizations of generation upon generation of philosophers and although one may argue that there is a long history of visual dominance, matters become vastly more complicated when taking a closer look at the available sources. First, although positioning vision first in his hierarchy, Aristotle also states that the sense of touch is "much more closely related than the other senses to the four elements, since the properties of the elements (dry, wet, cold, warm) are all palpable”, leading him to the conclusion “that without the sense of touch there could be no other senses” (Jütte, 2005, p. 42) – an idea Thomas Aquinas agreed with more than a thousand years later. Thus, one could claim that the hierarchy proclaimed by Aristotle was not meant to be interpreted that strictly after all. This idea is in line with Avicenna’s view on Aristotle. As the medieval, Persian polymath “understood it, what Aristotle meant was that with respect to honour the primacy of the sense of sight applied, but that from the point of view of natural aptitude the sense of touch merited priority” (Jütte, 2005, p. 69). Second, it can be demonstrated that the dominance of the visual – supposedly already existing in the times of Aristotle – was less pronounced for a long time, that is, that the non-visual senses have lost ground against sight in the course of the past centuries. Hence, rather than being a cultural constant, visual dominance turns out to be heavily influenced by human decision-making. I will illustrate this idea using three different examples.

First, consider the shift from an oral, hearing-dominated to a written, sight-dominated culture (e.g. McLuhan, 1962; Ong, 1967), which was a result of the “Gutenberg Revolution”. While knowledge was predominantly transmitted orally before the invention of the printing press, vision has become the common means of acquiring information since then. Note, that this shift from hearing to sight arguably also changed interactions between people: The oral transmission of knowledge – and of literature, by the way – requires at least two people (a teacher and a student; someone who is telling a story and someone who is listening to it); in contrast, reading a book does not require any personal interactions – you can do it entirely on your own.

Second, take the decrease of the importance of smell. As Classen (1993) points out, “[i]n the pre-modern West […], smell was associated with essence and spiritual truth, while sight was often deemed a ‘superficial’ sense, revealing only exteriors” (p. 7). Moreover, the strength of the odor of a plant was associated with its presumed medical power: In order to protect themselves against epidemic diseases such as the plague, people in the medieval ages often carried a pomander with them, as they believed that strong scents are an antidote against the odors of illness which were considered to be the cause of infection. The idea that scents are important was also mirrored in the design of monastery gardens of the time: Flowers were mostly grown for practical purposes, that is for cooking or producing medicine – and as their scent rather than their visual appearance was considered to carry its potency, they “were grown together with garlic, onions and other herbs and vegetables used in cooking” (p. 22). This slowly changed from the 16th and even more so from the 18th century onward: As the belief in the healing power of scents faded away and as gardens were also cultivated for aesthetical and recreational reasons, visuals became increasingly more important.[5] In a similar spirit, it has recently been argued that the idea that humans have a poor sense of smell "derives not from empirical studies of human olfaction but from a famous 19th-century anatomist's [Paul Broca] hypothesis that the evolution of human free will required a reduction in the proportional size of the brain's olfactory bulb" (McGann, 2017, p. 1). In contrast to this hypothesis, it has been shown that the olfactory abilities of humans are in fact quite good.

Third, imagine walking through a modern museum exhibiting sculptures: You would probably not in your wildest dreams think of touching these sculptures – and if you did, security guards, alarms, not to-be-crossed lines on the floor or transparent cases around the sculptures would remind you immediately that art is not to be touched (see Gallace & Spence, 2014 for the few contemporary counterexamples). In contrast to this, it has been observed that in medieval culture, sculptures were "far more publicly accessible" (Jung, 2010, p. 215). One may even say that sculptures were *meant* to be touched: "[M]edieval people stroked, held, and cradled sculptural representations" (Griffiths & Starkey, 2018, p. 9). Note, that remnants of these haptic worshipping traditions have survived until today: The right foot of the bronze statue of St. Peter in the St. Peter's Basilica in Rome is worn down by pilgrims who have touched and kissed it for centuries, for instance (for a description of similar rituals see Frijhoff, 1993).

As these three examples demonstrate, one can trace an ongoing shift towards vision throughout history. However, the bias towards vision may be even more pronounced in our present-day societies than ever before: Beginning with the invention of movies, cinema, and television and even more so in the face of the omnipresence of smartphones and computers, visual technologies increasingly regulate our daily lives:

> Modern life takes place onscreen. […] Human experience is now more visual and visualized than ever before from the satellite picture to medical images of the interior of the human body. […] In this swirl of imagery, seeing is much more than believing. It is not just a part of everyday life, it is everyday life. (Mirzoeff, 1999, p. 1)

To give one illustrative example, consider the now-common habit of taking a picture of your meal and of sharing it on social media before starting to eat. It has been hypothesized that this habit has profoundly changed the way restaurants are recommended. While recommendations used to be based on the opinion of friends and colleagues or on written reports in newspapers, magazines or reference guides like the famous "Guide Michelin", they are now increasingly based on the visual appearance of the food. This may ultimately lead chefs and restaurant owners to pay more attention to the visual arrangement of the food they serve, or even to prepare the food in a way that is going to look good on Instagram (see e.g. Lee, 2017; Saner, 2015; Spence, Okajima, Cheok, Petit, & Michel, 2016; for an experimental investigation of the importance of the orientation in the plating of food see Michel, Woods, Neuhäuser, Landgraf, & Spence, 2015). More broadly speaking, paying attention to visual aspects seems crucial to achieve important goals in life such as finding a job or a partner as well as improving social relationships – just think of the importance of visuals when presenting oneself on an online dating website, sharing holiday pictures on social media or applying for a job with a well-designed resume. In accordance with these kind of phenomena, the necessity of a "visual" or "pictorial turn" has been proclaimed in the cultural sciences (see e.g. Alloa, 2016; Boehm, 1994; Boehm & Mitchell, 2009; Mitchell, 1994). Such a visual turn can supposedly have a double function: it can account for the dominance of the visual by emphasizing the importance of research on the topic and it can help to create both an appropriate methodology to investigate and appropriate theories to describe the visual turn.

Overall, it seems that the dominance of the visual is not a cultural constant. It should not be forgotten, however, that everything that has been discussed so far primarily referred to – pre-modern, modern, and postmodern – *Western* cultures and societies. As it will turn out, considering non-Western societies only confirms the ideas presented so far: The dominance of the visual is at least partially the result of human decision-making and should thus not be regarded as an unvarying historical constant. Two examples shall suffice to illustrate the enormous cross-cultural variability.

First, a recent study has demonstrated that there is no universal hierarchy of the senses by investigating 20 different languages including three unrelated sign languages (Majid et al., 2018). The authors created stimulus sets for each of the five Aristotelian sensory modalities and asked their participants to describe them (What color is this? What sound is this?) in order to find out how detailed these stimuli are coded in each language. Apart from the fact that smell is poorly coded in most languages, there was no common hierarchy of the senses. While English indeed seems to have a visual bias (see the study by Winter et al., 2018, discussed above), other languages seem to have a gustatory bias (e.g. Turkish and Farsi) or a bias towards touch (e.g. Dogul Dom spoken in Mali and Siwu spoken in Ghana). Thus, the authors conclude, "that the mapping of language into senses is culturally relative" (p. 11374) and that "either by cultural tradition or by ecological adaptation, each language has come to concentrate its efforts on particular sensory domains" (p. 11375).

Second, let us examine one of the cultures for which sound seems to be more important than vision: the culture of the Songhay of Niger. It is important to note, that for them, sound is not only important because like in any oral culture, knowledge is transmitted by spoken words, but because the sounds of the words *themselves* are believed to carry energy and power:

> [The Songhay] believe that sound, being an existential phenomenon in and of itself, can be the carrier of powerful forces. […] We take the sound of language for granted. [The Songhay] consider language […] as an embodiment of sound which practitioners can use to bring rain to a parched village or to maim or kill their enemies. (Stoller, 1984, p. 569)

Thus, for the Songhay, "signifiers can function independently of their signifieds" (Howes, 1991, p. 10), that is, the meaning of a word and its sound can be separated and perform different functions.

What can we learn from considering the cultural explanation regarding the question why there is so much more research on vision than on any other sensory modality? The answer is quite simple: Living in a visual society means living in a society placing high value on vision and comparably little value on the other senses – a tendency that is mirrored in the number of studies on vision. Put differently, a society placing higher value on the other senses would probably develop more balanced research agendas (i.e. research agendas in which the bias towards vision would be less pronounced).

Conclusion: Living in a Visual Society and the Need for Integration

Why is there so much more research on vision than on any other sensory modality? This paper has discussed three different explanations. The only explanation that can be found in contemporary books on perception and cognitive psychology, which I have called the textbook explanation, claims that the reason for the bias towards vision is its importance and complexity. Although there are arguments in favor of this explanation, the validity of these arguments seems debatable as it crucially depends on the definition of importance and complexity. Apart from that, the textbook explanation is at least incomplete as there are other aspects that need to be taken into consideration. As the methodological-structural explanation proposes, the present-day technology is better suited for studying vision than for studying other modalities, which may be the result of a Matthew effect reinforcing the advantage of the visual. In addition to that, the cultural explanation suggests that the dominance of the visual is not an historical constant, neither in Western nor in non-Western societies, and should consequently be viewed as being influenced human decision-making. In my opinion, there a two important lessons to be learned from this outcome: the necessity of diversity and the necessity of integration. Let us consider both.

First, the necessity of diversity: Diversity is not necessarily good per se. In the event that there was in fact one modality, which is much more important and complex than all the others, a research bias towards this modality would be perfectly understandable (and a visual turn advisable). As "[a]ny classification of the senses is first and foremost an analytical device, a simplification and an abstraction" (Rodaway, 1994, p. 28), however, and as the dominance of the visual is at least partially a cultural construction, a call for more diversity seems justified. This is not only because the other senses deserve more attention, but also because the theories of perception and perceptual memory developed from studies on vision may in fact be theories on *visual* perception and *visual* memory, which do not capture the peculiarities of the other senses (see e.g. Barwich, 2019; Batty, 2011). It has been shown, for example, that "studies of multisensory processing have focused on a narrow region of space in front of the observer" (van der Stoep, Serino, Farnè, Di Luca, & Spence, 2016, p. 513), that is, that even the way non-visual stimuli are presented seems to be biased due to the dominance of vision in research. Thus, basing our theories of perception and perceptual memory mainly on vision may indeed lead to limited and impoverished conceptualizations of perceptual memory. As O'Callaghan (2011) puts it: "Attention to just one sense is bad policy if we're after a comprehensive and general account of perception, rather than a parochial story about vision" (p. 143).

Second, the necessity of integration: Although I have not explicitly stated this, the ideas presented in the present paper were by and large in line with the Aristotelian view that humans possess five senses. No more than the hierarchy of the senses, however, the number of postulated senses is the same across times and cultures (see e.g. Gold, 1980; Jütte, 2005). Rather, it seems that "[f]rom the invention of the alphabet there has been a continuous drive in the Western world toward the separation of the senses, of functions, of operations, of states emotional and political, as well as of tasks" (McLuhan, 1962, p. 42-43). Given that the different sensory modalities share significant parts of their neural underpinnings, given that the processing of information seems to be rather multimodal than unimodal, and given that our everyday experience is characterized by the concurrent stimulation of our senses, investigating their interactions seems more promising than trying to make more and more fine-grained distinctions (for the attempt to say more about the different kinds of interactions between the senses see e.g. Fulkerson, 2014).

Indeed, it has been shown that the integration and combination of the senses can have an important impact on educational outcomes (see e.g. Keehner, & Lowe, 2010; Reid, Shapiro, & Louw, 2019) – not to forget that multisensory integration plays a crucial role in several research areas on high-level cognition, such as the interactions between perception and action or embodied cognition. In the field of embodied cognition, for example, it is believed that “cognition depends upon the kinds of experience that come from having a body with various sensorimotor capacities, and […] that these individual sensorimotor capacities are themselves embedded in a more encompassing biological, psychological, and cultural context” (Varela, Thompson, & Rosch, 1991, p. 173), that is, that cognition cannot be understood without understanding the co-presence of these various sensorimotor capacities (for a similar, early account see Gibson, 1979; for a more recent perspective on embodied cognition see Shapiro, 2011).

All in all, investigating the seemingly easy to answer question as to why there is so much more research on vision than on any other sensory modality does not only lead us right into the middle of historical changes and cultural differences, but also gives us the opportunity to take a step back and to start thinking about visual dominance. If the degree to which vision dominates research on the different sensory modalities is not an unchangeable necessity, what kind of sensory environments do we want to create and what kind of research do we want to conduct?

Footnotes

[1] When speaking about “visual memory”, “auditory memory”, etc., I do not simply mean “memory for information acquired through vision/audition”, but memory for the perceptual qualities of a certain stimulation (i.e. perceptual memory).

[2] Although the distinction between distant and proximal senses is well established in the literature, one may argue that the distinction is not that strict after all, as one can feel the sun (i.e. a distant stimulus) one one’s back, for instance.

[3] This does not imply that we are consciously aware of *all* visual information. As phenomena like change blindness (Rensink, O’Regan, & Clark, 1997) or inattentional amnesia (Simons & Chabris, 1999) demonstrate, we often miss even significant changes in our surroundings. Nevertheless, vision seems to capture a far greater percentage of our attention than the other modalities (for an intuitive rule of thumb see Heilig, 1992).

[4] The idea that the available technology mediates how research questions are investigated, can also be made clear by looking at the history of attention research, for instance: For various theoretical reasons, but also because “multi-channel tape recorders became available at the time and provided an elegant way of presenting stimuli”, nearly all “all the early experiments on attention used auditory” (Styles, 2006, p. 16). This only began to change when computers started to spread all over the world.

[5] Just as the “eye-minded philosophy of the Enlightenment” (Classen, 1993, p. 27) changed the way of structuring and organizing gardens, it also changed the way people approached anatomical drawings (Massey, 2017), that is not only the way people thought about the non-visual senses, but also the way they thought about vision itself. Before the 18th century, there had been no apparent conflict between aesthetically appealing and practically useful anatomical drawings of the human body. Anatomical drawings were largely based on the writings of Galen and often contained allegorical depictions to foster the understanding of the human body. One may even say that the anatomical drawings – although being visual, of course – were *not about being visual* in the sense of an accurate depiction of reality, but about combining different aspects ranging from natural philosophy to religion and medicine as well as about activating different senses (see also Borland, 2018). This began to change in the age of Enlightenment: The new norm were accurate drawings based on exact observations, often made during dissections – while artistic depictions of the human body became a clearly separated category of their own. In other words, in the anatomy of the 18th century, the visual became *important as visual*.

3. General Discussion

3.1 Summary of Findings

In short, **Study 1** demonstrates that the memory representations stored in haptic long-term memory are detailed and robust over time. In Experiment 1, participants performed remarkably well on a memory test that required detailed knowledge about the presented objects in order to give a correct answer, no matter whether memory was tested immediately after the study phase (94% correct) or one week later (85% correct). In Experiment 2, encoding was incidental. However, memory performance was still high: When tested after one week, participants gave the correct answer in 79% of the trials (compared to 85% in Experiment 1). Interestingly, participants were able to use the incidentally and haptically encoded information in a crossmodal visual task with a very high accuracy (73% correct). Thus, after having haptically explored an everyday object (such as a pen) for ten seconds while being blindfolded, participants were able to distinguish this object from another object from the same basic-level category (i.e., another pen) in a purely visual memory test during which they were not allowed to touch the objects – although encoding had been incidental and the memory test was performed one week after the study phase. Another interesting pattern is revealed by the metamemory judgments provided by the participants in Experiment 2: Participants performed best when claiming that they had *remembered* the correct answer (unimodal haptic test: 94%, crossmodal visual test: 89%) and worst when claiming that they had purely *guessed* based on their intuition (unimodal haptic test: 66%, crossmodal visual test: 63%); performance in trials in which the participants had the feeling of *knowing* the correct answer was in between (unimodal haptic test: 78%, crossmodal visual test: 75%). At first glance, one may simply take this pattern as indicating that memory performance was better the more confident the participants were about their answer in the memory test. However, two more aspects need to be considered. First, participants performed very well on trials in which they believed they remembered the correct answer. Nonetheless, there was a fraction of trials in which participants were misled by their subjective impression of remembering the correct answer (unimodal haptic test: 6%, crossmodal visual test: 11%). Second, participants performed significantly above chance even on trials in which they had guessed solely based on their intuition. Taken together, these two observations both point to the conclusion that performance in the memory test was only partially accompanied by conscious awareness of their own memory abilities (see section 3.2.1 for a more detailed discussion).

Study 2 complements the findings from Study 1 by showing that detailed long-term memory representations are formed for incoming – in this case: auditory – information even if this perceptual information was unattended, irrelevant, incidentally encoded, and processed in a different modality than the attended information. No matter whether being tested immediately after completing the encoding phase or after 24 hours, participants performed significantly above chance (immediate test: 57%, delayed test: 56%). While previous studies have consistently found that no perceptual information is stored in long-term memory under these conditions, Study 2 does not only demonstrate that *some* information is retained, but that *detailed* information about prior perceptual experiences is retained. The crucial difference between Study 2 and the previous attempts to investigate the fate of unattended information was the way in which memory was tested. In the present study, participants indicated which of two sounds they believed they heard before (2AFC), while previous studies used old-new recognition tests (ONR), which are less sensitive and rely more on the conscious experiences of recollection and familiarity (see, e.g., Voss & Paller, 2010). As demonstrated by further analyses, the above-chance performance was driven neither by a few sounds nor by temporarily shifting attention from the visual to the auditory stream in the encoding phase. Thus, Study 2 challenges the assumption that the allocation of attention to the incoming perceptual information is a necessary precondition for storing detailed representations in perceptual long-term memory.

Although Study 1 and 2 were concerned with haptic and auditory long-term memory respectively, the vast majority of studies on perceptual long-term memory are studies on visual long-term memory. **Study 3** shows that this dominance of the visual cannot simply be explained by pointing to the ‘importance’ and ‘complexity’ of vision compared to our other senses. Both, ‘importance’ and ‘complexity’ are umbrella terms that encompass a wide range of different meanings. Importance, for instance, may mean ‘subjective importance’, that is, the importance of a sensory modality from a first-person point of view. However, it may also mean ‘importance for survival’, ‘importance in everyday life’ or ‘importance for the healthy development of a human being’. Considering these different meanings of ‘importance’ leads to different conclusions regarding the hierarchy of our senses. As demonstrated in Study 3, the same applies to arguments about complexity. Thus, the idea that there is so much more research on vision than on any other sensory modality because of the importance and complexity of vision is at least debatable. Apart from that, the answer is incomplete as there are other aspects that need to be considered. Study 3 discusses two of them. According to the methodological-structural explanation, the bias towards vision can be explained by the fact that research on vision is easier to conduct than research on the other senses. Although vision may be easier to investigate by nature, it is also possible that the methodological advantage, at least partially, has idiosyncratic reasons and is driven by the way rewards are allocated in research. Specifically, there is a tendency to give funding to well-researched topics and to be more hesitant to support less prominent fields of research – an attitude that reinforces existing biases. The second alternative explanation, the cultural explanation, points to the fact that the degree to which vision is perceived as the dominant sense is neither a historical nor a cultural constant. Although Western societies have placed a great emphasis on vision since antiquity, the importance of vision has arguably increased over time and even more so in the last few decades. Apart from that, there is apparently no universal hierarchy of the senses. Rather, different cultures place different emphasis on different senses. Taken together, the explanations discussed in Study 3 provide clear evidence that the dominance of the visual is heavily influenced by human decision-making.

3.2 Theoretical Considerations

The results of the three studies summarized above raise several theoretical issues, which are discussed in the following sections: first, the relation between perceptual long-term memory and conscious awareness; second, the question as to how perceptual long-term memory is related to implicit memory; third, the question as to how one can be sure that the stored details were *perceptual* rather than conceptual as well as the question as to what actually constitutes a *detail*; and fourth, the interactions as well as similarities and differences between our senses.

3.2.1 Perceptual Long-Term Memory and Conscious Awareness

As described above, performance in Study 1 was only partially accompanied by conscious awareness: Although participants performed very well on trials in which they had the subjective impression of remembering the correct answer, they still gave the wrong answer in a fraction of these trials. Even more importantly, participants performed clearly above chance on trials in which their answers were based purely on guessing. The notion that perceptual long-term memory representations may at least partially be independent from conscious awareness is also supported by Study 2. While previous studies using memory tests that rely on the conscious processes of recollection and familiarity have found null memory effects for irrelevant and unattended perceptual information under high attentional load, the present study provides evidence for detailed memory representations when using a more sensitive memory test. All in all, both Study 1 and Study 2 provide evidence that humans store detailed representations in perceptual long-term memory without being (fully) aware of these memory abilities.

However, how do the results fit with existing theoretical models of perceptual long-term memory? Two models shall be considered here: the *perceptual representation system* (PRS) and the *multiple-entry, modular memory system* (MEM). The PRS (Schacter, 1990; Tulving & Schacter, 1990) is conceptualized as a largely non-conscious memory system for the perceptual, in contrast with the conceptual aspects of processed perceptual information. While the PRS does "process and represent information about the *form* and *structure* of words, objects, and other kinds of stimuli, [it does] not represent *semantic* or *associative* information about them" (Schacter, 1990, p. 550). As the PRS-framework points to the possibility of remembering perceptual information without conscious awareness, it can help explain the results of Study 2: Other than the less sensitive memory tests used in previous studies, the 2AFC used in Study 2 did not solely rely on the conscious processes of recollection and familiarity because participants were explicitly encouraged to guess and to go with their 'gut feelings' (see, e.g., Voss & Paller, 2010). Thus, Study 2 was able to detect non-conscious memory representations as stored in the PRS. However, referring to the PRS-framework is not sufficient for fully explaining the data of Study 1. Admittedly, one may argue that participants managed to perform significantly above chance on trials in which they had purely guessed, because they had non-conscious access to information stored in the PRS. However, in about one third of the trials, participants indicated that they had remembered the correct answer, that is, that they had conscious access to the perceptual details that distinguished the two exemplars from one another. Crucially, participants were correct about their remember-judgment in the overwhelming majority of trials. Thus, it seems plausible to assume that they were aware of at least some of the information they had stored in perceptual long-term memory.

A memory model that allows for both conscious and non-conscious perceptual long-term memory representations is the MEM (Higgins & Johnson, 2012; Johnson, 1983; 2007; Johnson & Hirst, 1993). The MEM divides memory into four functional subsystems: two are perceptual subsystems (P-1 and P-2) while the other two are reflective subsystems (R-1 and R-2). As the studies described here were concerned with perceptual long-term memory, only the two perceptual subsystems will be considered in more detail. P-1 processes include "*locating* stimuli, *resolving* stimulus configurations, *tracking* stimuli, and *extracting* invariants from perceptual arrays" (Johnson & Hirst, 1993, p. 243) and typically operate below conscious awareness. In contrast, we are typically aware of P-2 processes, which are involved in "*placing* objects in spatial relation to each other, *identifying* objects, *examining* or perceptually investigating stimuli, and *structuring* or abstracting a pattern of organization across temporally extended stimuli" (Johnson & Hirst, 1993, p. 243). Put differently, P-1 processes typically deal with perceptual features of our environment, while P-2 processes enable us to learn "about the conscious, phenomenal perceptual world of objects such as people, chairs and balls, events such as seeing a person sit down in a chair or catch a ball, and the relations among objects" (Johnson, 2007, p. 354; for an empirical demonstration of the dissociability of P-1 and P-2 processes, see Spachtholz & Kuhbandner, 2017). Thus, it seems legitimate to speculate that perceptual information that is stored as a result of P-1-processing is represented in memory in the form of independent features, while perceptual information that is stored as a result of P-2 processing is represented in memory in the form of coherent objects (for an extended discussion of the storage format see section 3.3.2).

Most importantly, the differentiation between P-1 and P-2 processes can help explain the results from Study 1 *and* Study 2. As far as Study 1 is concerned, the fact that participants performed significantly above chance even when indicating that they had purely guessed could be explained by assuming that participants used P-1 processes to give the correct answer – processes they do not have conscious access to. In contrast, their performance on trials in which they indicated that they remembered the answer was arguably driven by P-2 processes they were consciously aware of. Note, however, that these speculations cannot be proved with the present data, as it remains unclear how the metamemory judgments relate to the processes underlying the actual memory performance. That is, the metamemory judgments may not necessarily mirror the underlying memory processes accurately.

As described above, Study 2 found evidence for detailed long-term memory representations for unattended, irrelevant and incidentally encoded auditory information, while previous studies had found null memory effects. This difference could be due to the fact that the recollection-and familiarity-based memory tests that were used in these previous studies required the participants to rely on P-2 processes, while the present study used a more sensitive memory test in the sense that relying on P-1 processes was sufficient for giving a correct answer. Thus, the MEM seems to potentially provide a framework for understanding the results of the present studies.

Note, however, that the present studies do not only fit with existing theories on perceptual long-term memory such as the MEM and (partially) the PRS, but that they also extend the knowledge about this memory system by showing that the stored representations are detailed, durable and created as a natural product of perception (i.e., even under incidental encoding conditions and when the attentional resources are fully exhausted by a concurrent task). Put differently, the present studies allow for concluding that both the quantity and quality of perceptual information stored in perceptual long-term memory is higher than previously believed (see, e.g., Brady et al., 2008).

3.2.2 How Is Perceptual Long-Term Memory Related to Implicit Memory?

To consider the relation between perceptual long-term memory and implicit memory, let us begin with definitions. While the term ‘explicit memory’ is commonly used to describe the memory system for the conscious recollection of prior experiences, the term ‘implicit memory’ is meant to describe those memories one is not consciously aware of (for a brief overview see, e.g., Mulligan, 2003). Instead of speaking of explicit versus implicit memory, one may also speak of declarative versus non-declarative memory: While declarative memory can further be divided into semantic and episodic memory, non-declarative memory encompasses procedural skills and habits, priming and perceptual learning as well as simple classical conditioning and reflexes (see Squire, 2004). So how do these distinctions relate to perceptual long-term memory?

As described above, perceptual long-term memory comprises both explicit and implicit memories. On the one hand, P-1 processing leads to memory representations one is unaware of, and which can thus be described as implicit; on the other hand, P-2 processing leads to memory representations one is typically aware of, and which should consequently be viewed as being explicit. Note, however, that just as not all perceptual memories are implicit, not all implicit memories are perceptual. To understand this, simply consider the example of semantic priming (for an overview see, e.g., Neely, 1991); that is, the observation that processing a prime (e.g., wolf) may facilitate the processing of a subsequent, semantically related target (e.g., dog). Thus, it seems that long-term memory representations can be either perceptual or conceptual, and at the same time either explicit or implicit.

When considering the results of the studies presented here, it was argued that performance was probably driven by a combination of P-1 and P-2 processes, that is, a combination of explicit and implicit memory processes. Although this speculation seems plausible given the results of previous studies (see, e.g., Spachtholz & Kuhbandner, 2017) and fits with the existing memory models, the present data are insufficient for proving it. Thus, more research is needed to disentangle implicit and explicit perceptual memory processes in order to being able to answer the question as to what drove memory performance in the tasks used in the present studies.

3.2.3 Are the Stored Details *Perceptual* – and What Is a Perceptual *Detail*?

In both Study 1 and Study 2, participants had to choose between two exemplars from the same basic-level category. To this end, Study 1 used everyday objects, while Study 2 used everyday sounds. It was argued that performing well on a 2AFC indicates that *detailed perceptual* memory representations have been stored. However, two questions need to be asked to better understand the results. First, how can one be sure that the participants' answers were driven by *perceptual* and not by *verbal-conceptual* knowledge? Second, what exactly does it mean that the stored memory representations were *detailed*?

At first glance, one may argue that the first question is easy to answer, as the fact that participants were at least partially unaware of their memory abilities clearly demonstrates that the stored information is represented on a perceptual rather than on a verbal-conceptual level. As described above, however, perceptual long-term memory is not necessarily memory without awareness. To use the MEM terminology: While P-2 processes are conscious, P-1 processes are not. Thus, one could rephrase the question as follows: How can one be sure that performance on trials in which participants were aware of their memory abilities was driven by perceptual rather than verbal-conceptual knowledge? The basic idea for disentangling perceptual and conceptual knowledge is simple: Performance was driven by perceptual and not by conceptual knowledge if the potentially available verbal-conceptual knowledge was not sufficient for distinguishing between the two stimuli.

As the pairs of objects in Study 1 and sounds in Study 2 belonged to the same basic-level category, simply remembering this basic-level category ("I touched a pen", "I heard the humming of a refrigerator") was insufficient for giving a correct response in the memory test. However, one may argue that participants created meaningfully different subtypes by verbally recoding the presented stimuli so that no detailed perceptual knowledge was necessary for distinguishing the two objects of a pair. Take the basic category item 'pen', for instance: Participants could define subordinate categories such as 'click-ballpoint pen' versus 'simple ballpoint pen' in order to differentiate between the two objects of a pair. In case they used this strategy, the argument goes, memory performance would be driven by conceptual and not by perceptual knowledge. However, this line of reasoning is flawed for several reasons.

Since the exemplars had to be distinguishable, the creation of ‘subtypes’ is theoretically possible ad infinitum as long as ‘subtype’ is defined by the differing attribute. Think of the pen example: Even when using two click ballpoints, subtypes like ‘click ballpoint with a metal clip’ versus ‘click ballpoint with a plastic clip’ can be formed; and even when using two click ballpoints with metal clips, the subtypes of ‘click ballpoint with a slightly curved metal clip’ versus ‘click ballpoint with a straight metal clip’ can be formed, and so on. Hence, the existence of subtypes is not a problem per se, but a fundamental principle on which recognition memory is based. Rather, it seems important to rule out the possibility that participants indeed used verbalization strategies to remember the stimuli.

As far as Study 1 is concerned, it is possible that participants have formed complex verbal descriptions during encoding in Experiment 1. Simply put, participants may have verbally recoded the haptic information in a way that enabled them to give the correct answer in the subsequent memory test (“I touched a click ballpoint with a slightly curved metal clip” versus “I touched a click ballpoint with a straight metal clip”). Crucially, however, intentional memorization strategies were ruled out in Experiment 2 by using an incidental encoding task. This makes it quite unlikely that participants formed complex verbal descriptions during encoding beyond basic-level categories, especially as the basic-level categories used in the present study corresponded to the granularity of everyday categories. Although intentional memorization strategies were ruled out, participants still performed far above chance. As the sounds were not only unattended, irrelevant, and incidentally encoded, but also rapidly presented in a continuous auditory stream in Study 2, the problem of verbal-semantic recoding does not arise. Thus, it seems that performance in both Study 1 and Study 2 was indeed driven by *perceptual* and not by verbal-conceptual knowledge about the stimuli – no matter whether participants were aware or unaware of their memory abilities on a given trial.

This brings us to the second question: Although the results of the present studies indicate that perceptual long-term memory stores detailed memory representations, it would be interesting to know *how detailed* the perceptual memory representations in fact are. To begin with, it is important to acknowledge that the similarity at the perceptual level was not varied systematically in the present studies. This is simply because it is hard to see how such a systematic variation could be accomplished. To understand why, consider the following example: Assume that you have a pair of hammers and a pair of belts. Further assume that one of the hammers is slightly newer than the other so that its surface is smoother; as far as the belts are concerned, one is a bit thicker and the form of the buckle is different. How could one determine whether the two hammers are more similar or less similar than the two belts?

There are two options: (1) asking participants for subjective similarity ratings and (2) trying to quantify the similarity psychophysically.

Although collecting subjective similarity ratings may seem like an easy way out, it is in fact not, for the simple reason that it would remain completely unclear on what basis participants make their similarity judgments, and whether their consciously made similarity judgments have anything to do with the differences and similarities that are extracted on a perceptual level. Trying to quantify the similarity of everyday objects as used in Study 1 or everyday sounds as used in Study 2 is also non-trivial. First, stimulus material taken from everyday life differs along many different dimensions: the everyday objects used in Study 1 differ regarding weight, form, texture, hardness, and elasticity, for instance, while the everyday sounds in Study 2 may differ regarding harmonicity, variation, rhythm, and so on. Even if one could measure these different stimulus properties independently, it remains unclear how these different measurements could be integrated into a single similarity score that is in line with the participants' perceptions. It is possible, for instance, that quantitatively small variations may lead to qualitatively big differences regarding the perceived similarity (see also the discussion of Study 2).

As this discussion makes clear, it is almost impossible to quantify the similarity of two everyday objects or everyday sounds. Thus, the present studies cannot answer the question as to how detailed the representations stored in perceptual long-term memory actually are. Exploring this question using laboratory-generated stimuli seems a promising avenue for further research. However, the advantages of using stimuli taken from everyday life should not be underestimated. When asking how many of the perceptual experiences that we make day in and day out are stored in perceptual long-term memory, it seems straightforward to use objects or sounds that are actually part of everyday experience. Stimuli taken from everyday life have an ecological validity that cannot be achieved using laboratory-generated stimuli.

3.2.4 The Beautiful Complexity of Our Senses

Our perceptual world is not only and probably not even predominantly a visual one – although people tend to believe that vision is their most important sense, and although most research on the different senses is research on vision. We are part of a rich perceptual environment and we constantly perceive information through all of our senses. While recent studies on visual long-term memory have demonstrated that not only a high quantity of information is stored, but also that the stored representations are highly detailed (e.g., Brady et al., 2008; Vogt & Magnussen, 2007), comparably little was known about perceptual long-term memory for the other sensory modalities. Thus, it remained unclear as to how well the rich perceptual environment is retained in perceptual long-term memory in a multisensory way. The evidence presented here can help to clarify this issue. While Study 1 demonstrates that the results found for visual long-term memory also hold true for *haptic* long-term memory, Study 2 shows accurate memory for perceptual details of *auditory* information. Taken together, Study 1 and Study 2 point to the importance of research on the non-visual senses: Fully capturing the richness and diversity of perceptual long-term memory is only possible when taking into account the contributions of all of the different senses.

These empirically motivated insights from Studies 1 and 2 are backed up by the considerations presented in Study 3: Other than what one may intuitively think, it is not clear that vision is indeed the most important and most complex sense. Rather, Study 3 supports the notion that the different senses capture different aspects of our environment and perform qualitatively different functions. Although – or maybe especially because – vision plays a prominent role in our everyday life and our Western societies are visual societies, a call for *diversity* seems well justified. Exclusively focusing on vision may lead to a one-sided and impoverished view of perception and memory.

At the same time, it is important to note that our senses hardly act independently outside the world of well-controlled laboratory settings. Normally, several senses are stimulated at the same time, leading to a perceptual experience that is perceived as a whole. For instance, I could not only *see* the craftsmen unloading materials from their van in front of my office, I could also *hear* them. I heard how they were pushing their toolboxes across the van's load floor and I heard a metallic sound of different tools bumping against each other when the toolbox was put to the ground. If I had opened the window, I also would have smelled the cigarette that one of the craftsmen was smoking. In other words, the perceptual experience of observing the craftsmen consists of the concurrent stimulation of several senses. Thus, the results of the studies presented here are not only a call for diversity, but at the same time also a call for *integration* and for considering multisensory interactions (see the discussion of Study 3). This can also be made clear by taking another look at Study 1 and the fact that performance in the crossmodal visual test was almost as good as performance in the unimodal haptic test. Although it is possible that the participants retrieved the haptic representations from memory and converted them into a visual format for the crossmodal memory test, it is also possible that the representations that were created in the encoding phase were rather amodal than haptic per se. Interestingly, recent brain-imaging studies support the second option, indicating that visual representations are automatically co-activated when haptically exploring objects (see Snow et al., 2014; Lacey & Sathian, 2014; see also the discussion of Study 1).

Understanding the complexity and multidimensionality of our senses is a challenging undertaking. However, ignoring it most certainly leads to theoretical models of perception and memory, which systematically underestimate the abilities of perceptual long-term memory and which are unable to capture the richness of the perceptual experiences that we permanently make.

3.3 Open Questions

The three studies described and discussed in this thesis open up new questions for future research, of which two shall be discussed in more detail in the next sections. First, not all incoming information seems to be stored in perceptual long-term memory – or at least not equally detailed. So what are the selection mechanisms that help us to distinguish between information that needs to be stored in high fidelity on the one hand and information that is less relevant on the other hand, if, as described above, the contents stored in perceptual long-term memory are only loosely tied to our current goals and intentions? Second, Studies 1 and 2 demonstrate that participants stored detailed long-term memory representations, as they were able to give the correct answer in memory tests that require considerably detailed memory representations to do so. However, what is the storage format of these detailed long-term memory representations?

3.3.1 Selection Mechanisms in Perceptual Long-Term Memory

The results of Study 1 and Study 2 show that detailed representations are stored in perceptual long-term memory. Although participants remembered the haptically explored objects remarkably well in Study 1, no matter whether memory was tested immediately after exploration or after one week, no matter whether participants knew that their memory would be tested or encoding was incidental, and no matter whether memory was tested in a unimodal or crossmodal memory test, their memory was not perfect. That is, participants did not remember all objects with the amount of detail required to distinguish between the two exemplars in a 2AFC. This pattern becomes even more obvious in Study 2. The fact that participants gave the correct answer in 57% of the trials in the immediate and 56% of the trials in the delayed memory test effectively means that participants remembered 14% and 12% of the sounds respectively.[5] In other words, 86% of the sounds in the immediate test and 88% of the sounds in the delayed test were not remembered correctly. What do these numbers mean?

Above all, these numbers do *not* mean that all objects that the participants remembered incorrectly in the 2AFC were forgotten. First, successfully distinguishing between the two exemplars from the same basic-level category required detailed knowledge about the sounds. In a similar study (Kuhbandner et al., 2017), it was demonstrated that performance was much better when less similar pairs of stimuli were used, indicating that more stimuli are stored in perceptual long-term memory albeit in less detail. Put in plain words, participants may not remember the humming of a refrigerator with enough detail to distinguish it from the humming of another refrigerator, but could still be able to indicate that they heard the humming of a refrigerator rather than the humming of an air conditioner, or at least that they heard the humming of a refrigerator rather than a bird singing. Second, although the 2AFC used in the present studies is – in contrast to an ONR, for instance – sensitive enough to detect detailed memories that the participants are not aware of, there could be other, even more sensitive memory tests potentially leading to even better performance. In this context, it is important to understand that the memory effects observed in Study 2 were actually not small – contrary to what one may initially think when hearing that about one in ten sounds was remembered correctly (see also the discussion of Study 2). In Study 2, the sounds were unattended, irrelevant, and incidentally encoded. That is, from a methodological point of view, everything was done to make successfully remembering the sounds as difficult as possible. Remember also, that previous studies have found null memory effects under such conditions. Thus, the results should be interpreted the other way around: *Although* the presented sounds were unattended, irrelevant, and incidentally encoded, participants still formed detailed perceptual long-term memory representations for about a tenth of them. In fact, storing detailed perceptual long-term memory representations of even a fraction of the incoming perceptual information challenges existing models of human memory and perception.

As the numbers described above neither mean that the memory effect was small, nor that unsuccessfully remembered stimuli were forgotten, one can repeat the question posed above with new emphasis: What *do* these numbers mean? Summed up in one sentence, the

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[5] Correct responses in a 2AFC include fortunate guesses. To correct for the effects of random guessing, the observed percentage correct ($PC_{Observed}$) can be converted into an adjusted percentage correct score ($PC_{Adjusted}$), using the formula $PC_{Adjusted} = 2 * PC_{Observed} – 100$. $PC_{Adjusted}$ estimates how often participants truly remembered a stimulus, after accounting for fortunate guesses (for details, see Brady, Konkle, Alvarez, & Oliva, 2013).

results of the present studies demonstrate that not all stimuli were remembered equally well and that some were stored with the amount of detail required for distinguishing two stimuli from the same basic-level category, while others were not. The question is: Why? Why were some stimuli stored in higher fidelity than others? What are the selection mechanisms that decide whether a stimulus is stored in high fidelity? At first, one may think that the results were possibly driven by certain stimuli characteristics that made the stimuli more or less memorable. Interestingly, however, above-chance performance in Study 2 was not driven by a few specific sounds. Instead, memory performance across the different sounds was normally distributed. That is not to say that stimuli characteristics do not play a role when it comes to storing information in perceptual long-term memory. On the contrary, exploring the role of stimulus characteristics in forming perceptual long-term memory seems to be a promising topic for future research. If the results of the present studies cannot be explained by specific stimuli properties, however, what else could be potential selection mechanisms?

One possible explanation is provided by the so-called ‘attentional boost effect’ (e.g., Swallow & Jiang, 2010; 2011; 2012; 2014; for a review, see Swallow & Jiang, 2013). In the typical attentional boost paradigm, participants perform two concurrent but unrelated tasks. One task is to view a series of images and to remember them for a later memory test. The other, concurrently executed task is to press a button when a target (e.g., a red square) appears in a series of distractors (e.g., squares of different colors). Although the two tasks are completely unrelated, memory performance for images that were paired with a target in the concurrent task were remembered better in a subsequent memory test than those that were not. It is argued that this attentional boost effect is best understood as a processing enhancement, that is, “that the selection of behaviorally relevant events in time produces brief, but broad, enhancements in perceptual processing, thereby facilitating the processing of the target and concurrent, but unrelated, background images” (Swallow & Jiang, 2014, p. 1298). There are two possibilities as to what a ‘behaviorally relevant event in time’ could be: either perceiving a target *stimulus* while concurrently viewing an image or providing a *response* to a target stimulus while concurrently viewing an image. Assume that the window of my office was open when observing the craftsmen, and further assume that one of them lights a cigarette, for instance. The behaviorally relevant event in time could either be the moment in which I smell the smoke (i.e., the moment in which I perceive the stimulus) or the moment in which I stand up and close the window, because I do not like the smell of cigarettes (i.e., the moment in which I respond to the stimulus). However, the existing studies on the attentional boost effect do not differentiate between these options, as the stimulus that participants see when a target appears is always also the stimulus that participants respond to. Thus, exploring whether the enhancement by the attentional boost effect is stimulus-based or response-based seems to be an interesting topic for future research.

Another potential selection mechanism can be derived from research in the field of task-irrelevant perceptual learning (for reviews, see Seitz & Watanabe, 2005; Seitz & Dinse, 2007; Watanabe & Sasaki, 2015). As the name already suggests, task-irrelevant perceptual learning describes the phenomenon that perceptual learning occurs even for aspects of the perceptual environment that are not relevant to the present task. Many efforts have been made to clarify under which conditions task-irrelevant learning can occur. While it was initially believed, for example, that task-irrelevant perceptual learning can only occur when it is linked to active, goal-directed behavior, it has been demonstrated "that visual learning can be formed in human adults through stimulus-reward pairing in the absence of a task and without awareness of the stimulus presentation or reward contingencies" (Seitz et al., 2009, p. 700). Thus, further investigating the role of reward contingencies in the forming of perceptual long-term memory representations is another possible topic for future research.

To sum up, given the results of the present studies, the question arises as to what the potential selection mechanisms could be that are responsible for deciding which stimulus is stored in high fidelity in perceptual long-term memory, and which is not. Although there may be certain stimulus characteristics that make some stimuli more memorable than others, such a mechanism cannot explain the results described here. Thus, there have to be other selection mechanisms. Two potential ideas were discussed here: the attentional boost effect and the role of rewards.

3.3.2 The Storage Format of Perceptual Long-Term Memory Representations

From a theoretical point of view, it seems that perceptual information can be stored in at least two ways: as independent features or as coherent, bound objects (see Spachtholz & Kuhbandner, 2017). At lower sensory-perceptual levels of the processing hierarchy, sensory information from the senses is analyzed along several basic dimensions. Based on this analysis, feature-based representations are created and stored that accurately mirror the physical properties of the original sensory input. At higher sensory-perceptual levels, the independent features are integrated into coherent objects. This is done by removing redundant sensory-perceptual information and by recoding the feature-based representations so that they fit with the perceptual model of the world that we constructed based on prior learning experiences (e.g., Riesenhuber & Poggio, 1999; Serences & Yantis, 2006).

Such a distinction between feature-based and object-based representations in long-term memory as proposed and demonstrated by Spachtholz and Kuhbandner (2017) clearly resembles the difference between P-1 and P-2 processes in the MEM-framework (see above, section 3.2.1). While P-1 processes can be described as leading to feature-based representations, P-2 processes seem to result in object-based representations. Although the studies presented here did not explicitly investigate in which format the detailed memory representations were stored and although more research is needed to disentangle P-1 and P-2 processes as well as feature-based and object-based representations, it is interesting to deliberate as to whether the results of the present studies can be understood from the perspective of such a framework.

As discussed above, one may speculate that performance in Study 1 was arguably driven by non-conscious P-1 processes on guess trials and at least partially driven by conscious P-2 processes on remember trials. Assuming that P-1 processes are linked to feature-based representations, while P-2 processes are linked to object-based representations, one could further speculate that performance in the memory test was the result of a combination of feature-based and object-based perceptual representations. The situation for Study 2 is slightly different: As hypothesized above, the 2AFC used in the present study differs from the previously used ONR insofar as the 2AFC is sensitive to non-conscious P-1 processes, while an ONR requires conscious access to the stored perceptual information and is thus sensitive to P-2, but not to P-1 processes. Following the line of thought presented here, the fact that a test is needed that is sensitive to P-1 processes to find above-chance performance for unattended, irrelevant and incidentally encoded perceptual information suggests that participants stored feature-based, but not object-based representations of the everyday sounds. This conclusion is in line with the widely held belief that attention is a necessary precondition for creating object-based representations (e.g., Treisman & Gelade, 1980).

All in all, the results of Study 1 and Study 2 do not only fit well with the distinction between P-1 and P-2 processes, but also with the idea that P-1 processes are linked to feature-based representations, while P-2 processes are linked to object-based representations. Thus, it indeed seems to be an interesting topic for future research to further investigate these theoretical distinctions. Apart from distinguishing the different processes and associated types of representation, it would also be fascinating to know more about possible interactions between the different instances.

3.4 Possible Applications

The results of the present studies suggest that humans possess a detailed perceptual long-term memory with an (in principle) unlimited storage capacity. In particular, storing information in perceptual long-term memory seems to be an effortless process and a natural product of perception. If this is true, however, exploring how this memory system can be used in real-world settings seems promising. In other words, the results of the present studies are not only relevant from the perspective of basic research, but could also have implications for designing practical applications and for fostering educational processes. The following two sections tentatively explore two fields in which interventions and programs based on perceptual memory skills could potentially turn out to be beneficial: (1) the broad field of learning and knowledge acquisition and (2) the case of people with dementia.

3.4.1 Learning and Knowledge Acquisition

According to the MEM framework (see section 3.2.1), perceptual information is not only passively stored in perceptual long-term memory, but also actively used for learning or, more precisely, for adjusting our behavior. As Johnson (2007) puts it, “learning via P-1 processes allows us to adjust to a person’s accent or to anticipate the trajectory of a baseball”, while learning via P-2 processes means – as already quoted above – “learning about the conscious, phenomenal perceptual world of objects […], events […], and the relations among objects” (p. 354). Thus, one may speculate that storing detailed memory representations in perceptual long-term memory as a natural product of perception is not simply a peculiarity of human cognition, but a functional mechanism that supports the fine-tuning of motor actions (e.g. grabbing a glass from a shelf without letting it slip, hitting a perfect tennis backhand down the line, etc.). As the present studies only show *that* detailed representations are stored in perceptual long-term memory, but do not allow for any conclusions regarding the functionality of such a memory system, more research is needed to investigate how perceptual long-term memory contributes to our behavior.

However, one may take the speculations even one step further and hypothesize that perceptual long-term memory does not only help improving *perceptual skills*, but also performance on complex *cognitive* tasks. That is, perceptual long-term memory may help fostering the acquisition of semantic-conceptual knowledge. Although such a speculation may initially seem a bit far-fetched, it is supported by constructivist theories of situated cognition, which claim – broadly speaking – that knowledge is not passively transmitted but actively and individually constructed under the specific conditions of a given environment (see, e.g., Gerstenmaier & Mandl, 1995; Knuth & Cunningham, 1993; Mandl & Gerstenmaier, 2000). In particular, theories of situated cognition hold that properly acquiring semantic-conceptual knowledge is bound to having the opportunity to connect this highly abstract and symbolic knowledge to real-world experiences (e.g. Resnick, 1987). Under such a perspective, including perceptual experiences in educational settings is an important precondition for knowledge acquisition. Interestingly, the hypothesis that perceptual learning may improve performance in complex cognitive tasks was tested in the context of knowledge acquisition in mathematics (see, e.g., Kellman, Massey, & Son, 2009; Landy & Goldstone, 2007). The basic idea is that dealing with mathematical problems crucially depends "on pattern recognition and fluent processing of structure, as well as mapping across transformations (e.g., in algebra) and across multiple representations (e.g., graphs and equations)" (Kellman & Massey, 2013, p. 125) and that these abilities can be fostered by perceptual learning.

In addition, consider another, completely different example: teaching anatomy to medical students. A proper understanding of human anatomy requires both semantic-conceptual knowledge and an accurate three-dimensional mental representation of the anatomical structures (see, e.g., Keenan & ben Awadh, 2019). Against this background, further fostering the physical, that is visual and haptic interaction with anatomical parts in addition to learning about anatomical structures by memorizing annotated, two-dimensional illustrations in anatomy atlases has become an important goal of methods developed in recent years (for a theoretical account, see Keehner & Lowe, 2010; for a practical implementation see Reid, Shapiro, & Louw, 2019). In particular, these approaches hypothesize that generating perceptual experiences through the multi-sensory observation of anatomical structures does not only improve perceptual and dexterity skills, but also allows for the semantic-conceptual understanding of anatomical structures.

All in all, it seems legitimate to speculate that storing detailed representations in perceptual long-term memory as a natural product of perception has a functional value and can consequently be used in educational settings. Crucially, perceptual long-term memory may not only contribute to perceptual, but also to semantic-conceptual learning. Note, however, that the results of the present studies cannot prove these speculations. Rather, they provide a starting point for future investigations.

3.4.2 Dementia

Although there are huge differences between the various forms of dementia, memory loss is a key characteristic in all of them. Interestingly, semantic-conceptual memories seem to be more affected by the disease than perceptual memories (see, e.g., Fleischman, Wilson, Gabrieli, Schneider, Bienias, & Bennett, 2005; Harrison, Son, Kim, & Whall, 2007; for a philosophical account, see, e.g., Fuchs, 2018; for an in-depth discussion of the issues presented in the following paragraphs, see Hutmacher, 2020). In this context, Fuchs (2018) argues that people with dementia still have access to an extremely rich and embodied inner perceptual world – even in the later stages of the disease, and although they may have lost many of their explicit and especially many of their semantic-conceptual memory skills. If this were true, this would open up at least two interesting possibilities.

First, in case people with dementia indeed still possess detailed memories about their past, albeit not in semantic-conceptual, but rather in perceptual form, one could try to base interactions on these remaining perceptual memories. Put differently, people with dementia may profit in terms of well-being from perceptual stimulation that is in line with their previous experiences as well as their current preferences (for reviews, see Sánchez, Millán-Calenti, Lorenzo-López, & Masseda, 2013; Strøm, Ytrehus, & Grov, 2016). Although this idea sounds promising, it has repeatedly been noted that many of the studies conducted so far lacked methodological rigor and that there are many interventions for which it remains unclear whether they are actually effective (Sánchez et al., 2013; Strøm et al., 2016). Thus, further investigating what aspects of perceptual long-term memory are preserved in people with dementia and how these perceptual memories can be accessed in everyday interactions seems to be a promising topic for future research, also in light of the results of the studies presented here, which show how rich and detailed perceptual long-term memory is in healthy subjects.

Second, in case people with dementia not only possess detailed memories about their past, but are also able to learn *new* skills using their remaining perceptual memory abilities, this would open up many possibilities in dementia care. In fact, people with dementia seem to show intact habit learning (see, e.g., Eldridge, Masterman, & Knowlton, 2002) such as learning new dance moves (Rösler, Seifritz, Kräuchi, Spoerl, Brokuslaus, Proserpi, Gendre, Savaskan, & Hofmann, 2002). In fact, it has become quite common in recent years to base the conception of environments and interventions for people with dementia on perceptual qualities (see, e.g., Davis, Byers, Nay, & Koch, 2009; Marquardt & Schmieg, 2009; Mitchell, Burton, & Raman, 2004; Mitchell, Burton, Raman, Blackman, Jenks, & Williams, 2003).

Feddersen (2014) describes, for instance, why it is important to consider the fact that people with dementia focus on the perceptual rather than on the semantic-conceptual aspects of their environment when designing nursing homes:

> For people with dementia, sensory experiences play a central role. This applies especially to how we experience space. […] When we design architecture for people with dementia, we must therefore take a step back and consider what is fundamental about the spaces we live in. (p. 15)

However, to date, the way perceptual memory and perceptual learning function in people with dementia is still not completely understood, although suggestions have been made and research has been conducted (see, e.g., Fleischman et al., 2005; Harrison et al., 2007). In particular, it remains unclear (1) whether the perceptual skills of people with dementia are comparable to the perceptual skills of healthy human beings or whether they are simply less impaired than their semantic-conceptual skills and (2) what exactly the perceptual qualities are that people with dementia use to orient themselves in their environment. Thus, systematically investigating perceptual memory in people with dementia seems to be an important goal for future research, as it may deepen the understanding of the disease and inform the development of real-world applications.

3.5 Conclusion

I am almost done now. These are the last sentences of my thesis. Thus, I take a short break to contemplate the moment. It is quite late already. My colleague has left the office about an hour ago. As the students are heading home from university, it is slowly getting calm and silent around me. The world outside the window starts fading into darkness. I wonder: What can be learned from this dissertation after all? What is the bottom line? As there is no one around to answer the question for me, I do it myself: The bottom line is that the world outside the window is actually *not* fading into darkness. While sitting at my desk, I have not only written this thesis, but also processed and stored a lot of perceptual information. I have seen the tree close to my window, the branches and leaves gently dancing in the wind, I have seen parked cars and parts of the university buildings, I have seen people passing by and craftsmen unloading materials from their van. I have felt the warmth of the cup of coffee in my hands, I have written several pages of notes with various pens, pressed a lot of keys on the keyboard, and tried to ignore the conversation my colleague had with a student. Subjectively, I may have the impression that most incoming perceptual information is either not processed at all or rapidly forgotten. In fact, however, it seems that storing information in perceptual long-term memory is an effortless and natural product of perception. Beyond the world of rational, semantic, and conceptual information, I am consciously aware of, there is a world full of detailed perceptual memories from all my senses I may not – or at least not always – have conscious access to, but which nevertheless helps me guide and adjust my behavior in everyday life.

Acknowledgments

Ich danke Herrn Prof. Dr. Kuhbandner für die persönlich wie fachlich bereichernde Begleitung auf meinen ersten Schritten hinein in die Welt der Forschung – und insbesondere für das außergewöhnliche Maß an akademischer Narrenfreiheit. Herrn Prof. Dr. Peter Fischer danke ich für die bereitwillige Übernahme des Zweitgutachtens.

Für die zahllosen gemeinsam verbrachten und durchdiskutierten Mittags- und Kaffeepausen sowie die familiär-freundschaftliche Atmosphäre danke ich allen aktuellen und ehemaligen Mitgliedern des Lehrstuhls: Elizabeth, Ferdi, Iris, Julia, Kathrin, Lisa, Markus, Marlis, Moni, Philipp, Regina und Roland – ohne euch hätte diese Reise höchstens halb so viel Spaß gemacht.

Außerdem danke ich Simone Merk für die inspirierenden interdisziplinären Erkundungsgänge, meinen Eltern für die stete Begleitung und Ermunterung – bei Weitem nicht nur während der vergangenen dreieinhalb Jahre – sowie meinem Bruder, Felix Hutmacher, und seiner Freundin, Wiebke Böhmer, für unsere wunderbare Familien-WG und die unzähligen Gespräche über dampfenden Kochtöpfen. Nicht zuletzt danke ich Aliz Horváth für all die Kleinigkeiten und Großigkeiten, für die es sich lohnt, hier zu sein.

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