Touch this Wisely – You May Want to Know More…

How the Haptic Sense May Enhance Learning Experiences and Learning Outcomes

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Table of Contents

Summary

Multimedia learning theories (e.g., CATLM, Moreno & Mayer, 2007) focus on the visual and auditory sensory channels as access to learning materials. The haptic sense often plays a subordinate role. In particular, touching three-dimensional objects and the influence of this haptic experience on learning and the learning experience often receives little attention, even in empirical research.

The goal of this thesis was to address this research gap. Using a multi-criteria approach, I investigated to what extent the (additional) haptic exploration of exhibition objects in an experimental exhibition affects cognitive as well as motivational-affective outcomes. Three studies with a total of over 500 participants form the empirical basis for this. Two of these studies were conducted in the laboratory; the third study was a field study in the Deutsches Museum in Munich. For all studies, an experimental exhibition on the topic of animal husbandry, breeding, and welfare was set up and sensory access to the exhibition objects was systematically varied. The results of the studies show that the haptic experience has a positive effect on the recall of the exhibition objects. However, the haptic experience does not facilitate the acquisition of further, object-related knowledge, which was assessed with the help of knowledge acquisition tests. At the motivational-affective level, mixed findings were revealed.

This dissertation begins with a theoretical framing of the haptic sense and two practical examples for the use of haptic experiences in learning. This is followed by an overview of empirical studies. In the third and final section, the results are discussed, strengths and limitations are pointed out, and outlooks and ideas for further research are presented.

Zusammenfassung

Theorien zum Lernen in multimedialen Lernumwelten (z.B. CATLM, Moreno & Mayer, 2007) legen ihren Fokus auf den visuellen und auditiven Sinneskanal als Zugang zu Lernmaterialien. Der haptische Sinn spielt dabei oft eine untergeordnete Rolle. Insbesondere das Anfassen von dreidimensionalen Objekten und der Einfluss dieser haptischen Erfahrung auf das Lernen und die Lernerfahrung findet häufig – auch in der empirischen Forschung – wenig Berücksichtigung.

Das Ziel dieser Arbeit war es, an dieser Forschungslücke anzuknüpfen. Ich untersuchte mithilfe eines multikriterialen Ansatzes, inwiefern die haptische Exploration von Ausstellungsobjekten (zusätzlich zum Betrachten derselben) in einer Experimentalausstellung auf kognitive sowie motivational-affektive Variablen wirkt. Für meine Untersuchungen bilden drei Studien mit insgesamt über 500 Teilnehmenden die empirische Basis. Zwei dieser Studien wurden im Labor durchgeführt, die dritte als eine Feldstudie im Deutschen Museum in München. Für alle Studien wurde der sensorische Zugang zu den Ausstellungsobjekten in einer Experimentalausstellung zum Thema „Nutztierhaltung" systematisch variiert. Die Ergebnisse der Studien zeigen, dass die haptische Erfahrung einen positiven Effekt auf die Erinnerungsleistung an die Ausstellungsobjekte hat. Sie erbrachten jedoch keine Evidenz für die Annahme, dass die haptische Erfahrung den Erwerb von weiterem, objektbezogenen Wissen erleichtert, das mithilfe von Wissenstests abgefragt wurde. Auf motivational-affektiver Ebene zeigten sich gemischte Befunde.

Die vorliegende Arbeit beginnt mit einer theoretischen Einordnung des haptischen Sinns und zwei praktischen Beispielen für den Einsatz von haptischen Erfahrungen beim Lernen. Es folgt ein Überblick über die genannten empirischen Studien. Im dritten und letzten Abschnitt werden die Ergebnisse diskutiert, Stärken und Grenzen aufgezeigt sowie Ausblicke und Ideen für weitere Forschung präsentiert.

General Introduction

Human beings perceive their environment through their senses: They see the tree, hear the buzzing of the bee, taste the strawberry, smell the freshly mowed lawn, and feel the grass between their fingers. These sensory impressions are then integrated into an overall impression of a picnic on a perfect summer day. Of course, each single sensory channel is important for human perception, still the haptic sense has long been strongly under-researched, so it builds the focus of this thesis. Thereby, the central question is to what extent the haptic sense – in combination with the visual and auditory senses – supports the learning experience and learning in an informal learning setting.

In the following sections of the general introduction, the haptic sense is introduced and subsequently the theoretical basis of the current work is presented. Afterwards, I provide two prominent instructional approaches of learning with a haptic experience. The general introduction concludes with an overview of benefits of haptic exploration. Subsequently, I describe the three studies that constitute the empirical work of this thesis. In the third and last part of the thesis, the results are summarized, limitations are discussed, and future directions are presented.

The Haptic Sense

It is impossible to imagine our everyday life without the haptic sense. It supports our interpersonal interaction through handshakes and hugs; it helps us at night not to lose our orientation in the dark apartment in order to find the bathroom; it plays an important role in buying decisions, for example when comparing the texture of two t-shirts; it enables us to manually explore unfamiliar objects and thus understand their functionality, for example when trying to install and adjust the brakes of a bike.

The haptic sense is the first sense through which humans perceive their environment, and it is central to our development (Field, 2003). Field (2003) states: “Infants and young children are dependent on touch for learning about the world. During the first year of life, everything goes in the mouth and is learned through the mouth's touching." (p. 8). Whereas the visual, auditory, and olfactory senses work well from a distance, the haptic sense brings us into direct contact with fellow human beings, objects, and the environment. Taylor and colleagues (1973) stated that the haptic sense is the "reality sense" (p. 270), meaning that things that can be touched are more likely to be real for us than things that can only be seen. In support of this statement, Wing and colleagues (2007) explain: "Vision often appears to determine the way we perceive the world. However, touch is the sensory modality that verifies the reality of what we see by allowing us to confirm the physical presence of objects and people around us" (p. 31). Accordingly, the haptic sense as a decisive component for interaction with the environment and fellow human beings is an essential part of our multimodal system (Minogue & Jones, 2006; Smith & Gasser, 2005).

It is generally assumed that the haptic perceptual system consists of two subsystems: the cutaneous and the kinesthetic (Lederman & Klatzky, 2009, Loomis & Ledermann, 1986). While the cutaneous subsystem receives input from receptors located in the skin, the kinesthetic subsystem receives input from receptors embedded within muscles, tendons, and joints. The haptic system combines the perception of both subsystems.

In the literature on the sense of touch, passive and active touch are commonly distinguished from one another (Gibson, 1962; Loomis & Lederman, 1986; Minogue & Jones, 2008). Passive touch describes situations in which one is being touched by a person or a stimulus. For example, the experience of holding an object up to the skin. In contrast, "active touch is an exploratory rather than a merely receptive sense" (Gibson, 1962, p. 477) which means that someone chooses to explore and manipulate an object with the hands to provide information about the object's characteristics.

Lederman and Klatzky (1987) distinguish different exploratory procedures that describe stereotypical hand movements adults use to explore objects with the haptic sense to get such information on their properties. Eighteen blindfolded participants were asked to explore three dimensional objects with their hands and choose which from three comparison objects matches best. By analyzing the hand movements and accuracy, typical exploratory procedures were identified for gaining a certain information about an object. For example, pressure can be used to get information of the object's hardness, whereas following the contour can be used to receive details about shape and volume (Lederman, & Klatzky, 1987; 2009). These forms of exploration maximize the sensory input and support the encoding process. Lederman and Klatzky (1987) explain that "hand movements can serve as 'windows', through which it is possible to learn about the underlying representation of objects in memory and the processes by which such representations are derived and utilized" (p. 342).

Although the importance of the haptic sense is obvious, it is way less researched than the visual and the auditory sense (Gallace & Spence, 2009, Hutmacher, 2019). Gallace and Spence screened the PsychINFO database for the number of studies that were published between 1806 and 2007 and contained visual, auditory, olfactory, gustatory, or tactile/haptic memory in the title. On one hand, they found that there were more studies on visual memory than on all other sensory modalities together, and on the other hand, even though there were a substantial number of studies on the auditory memory, the number of studies on olfactory, gustatory, or tactile/haptic memory was very limited. Hutmacher (2019) repeated this search for studies published since 2008 (until 2019) and found a similar pattern. Hence, there clearly is a lack of research that focuses on the haptic sense. In particular, more research is needed on whether and how the haptic sense can support learning processes (Minogue & Jones, 2006).

Theoretical Underpinnings: Multimedia Learning

Even though the haptic sense plays an important role in our everyday life, it is not sufficiently considered in learning theories, especially in multimedia learning theories. There are several theories that explain effects of learning with multimedia material by mainly focusing on combinations of textual and pictorial material, including the cognitive load theory (CLT) by Sweller and colleagues (e.g., Paas & Sweller, 2014), the integrative model of text and picture comprehension by Schnotz (2014), the cognitive theory of multimedia learning (CTML) by Mayer and his colleagues (Mayer, 2014), and the cognitive-affective theory of learning with media (CATLM) by Moreno and Mayer (2007). Although the modality effect states that learning will generally be enhanced when the learner receives input from different channels, the empirical work as well as theoretical arguments have mainly focused on combinations of visual and auditory information in these models (Ginns, 2005). Input via other sensory channels remained largely unconsidered so far. Furthermore, the theories mentioned concentrate primarily on the cognitive steps required for the appropriate processing of multimedia learning material, beginning with the perception and selection of information, through its organization, elaboration, and integration in working memory, and finally ending with its transfer to and retrieval from long-term memory.

For this thesis, the CATLM (Moreno & Mayer, 2007) serves as a theoretical framework. As an extension of the CTML (Mayer, 2014), it adopts its basic assumptions, namely, (1) information processing uses two or more channels (Baddeley, 1992; Paivio, 1986), (2) the capacity of working memory is limited (Sweller, 1999), and (3) active knowledge construction and active information processing forms a prerequisite for successful learning (Mayer & Moreno, 2003), and expands them by four additional assumptions, including (a) that long-term memory consists of a semantic and an episodic memory and has a dynamic structure (Tulving, 1977), (b) that learning is mediated by motivational and affective factors by increasing or decreasing cognitive interrelations with the content (Pintrich, 2003), (c) that metacognitive factors are supposed to influence learning with multimedia by regulating cognitive and affective processes (McGuinness, 1990), and (d) that differences in prior knowledge and abilities of learners influence learning success (Kalyuga et al., 2003).

Not only do these extensions of the assumptions bring motivation and affect into greater emphasis, CATLM also offers an extension in terms of input modalities. Along with the relevance of the auditory and visual channel as input modalities, the tactile, olfactory and gustatory senses are also seen as a potential additional source of information that can impact the learning process (Chan & Black, 2006; Moreno & Mayer, 2007). Hence, CATLM stresses the value of touchable materials as an educational tool. Figure 1 illustrates the theory (adapted from Moreno and Mayer, 2007). On the one hand the figure shows the extension by the three further sensory channels – the haptic, olfactory and gustatory sense – and on the other hand it depicts the role of motivation and affect. Three-dimensional or real objects such as exhibits in museums are not considered and are therefore supplemented by me.

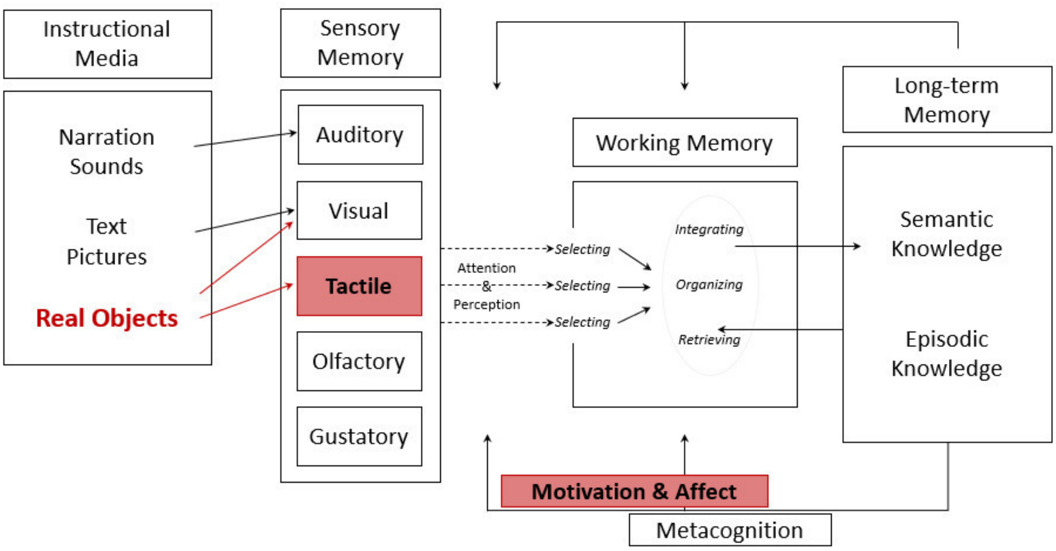

Figure 1: The cognitive-affective model of learning with media (adapted from Moreno & Mayer, 2007; highlights added by myself).

Paas and Sweller (2012) reinforce the assumption that the haptic sense can impact learning by claiming that object handling is a form of prioritized learning that supports the acquisition of biologically primary knowledge. Inspired by Geary's (2008) evolutionary educational psychology, Paas and Sweller suggested an evolutionary upgrade of the CLT which includes the distinction between biologically primary and secondary knowledge. While biologically primary knowledge refers to abilities that humans acquire in an effortless, uninstructed, unconscious, rapid, and intrinsically motivated way and without straining the working memory, biologically secondary knowledge, in contrast, is all knowledge that needs to be taught by others and learnt at the cost of cognitive resources. This knowledge is not evolutionarily relevant and often even so complex that it cannot be learned automatically. Examples for biologically secondary knowledge are skills like reading or writing. Paas and Sweller argue that biologically primary knowledge can be used to acquire biologically secondary knowledge, for example by an embodied cognition approach (Paas & Sweller, 2012; Pouw et al., 2014).

There are various learning situations/methods in which biologically primary knowledge can support the acquisition of biologically secondary knowledge such as finger tracing (e.g. Agostinho et al., 2015; Ginns et al.; 2016; Ginns, & Kydd, 2019; Hu et al., 2015; Macken, & Ginns, 2014; Tang et al., 2019; Yeo & Tzeng, 2020), hands-on experiments (Zacharia, 2015), touchable three-dimensional molecule models (Smith, 2016; Stull et al., 2018), interactive or touchable exhibits in science museums (Afonso and Gilbert 2007; Skydsgaard et al. 2016), and learning materials with a haptic component (Bara et al., 2004). In the following sections, two of these examples will be dealt with in more detail: Finger tracing and the role of haptics in museums.

Two Prominent Instructional Approaches of Learning with a Haptic Experience

Montessori Education and the Tracing Technique

Maria Montessori (1870-1952) was one of the most famous reform pedagogues of the 20th century. One central design principle in Montessori education is that learning should include all senses. Therefore, most learning materials are designed in a way that more than one sense is engaged and that sensorimotor experiences are incorporated into the learning process (Klein-Landeck & Puetz, 2019). Montessori was convinced that the movement of the body and cognition are closely related (Lillard, 2018).

One prominent example of a Montessori technique is the use of sandpaper letters in reading education (Montessori, 1912). Here, multimodality of the learning materials is perfectly realized: Students feel the way the letter is written as they trace its contours, and at the same time they look at its shape and hear the phonetic sound of the letter. Bara and colleagues (2004) investigated this teaching technique empirically with sixty monolingual French children with a mean age of five years and seven months. All participants were pre-readers and had no prior training with phonological tasks. The children were assigned to one of three seven-session training interventions. Whereas letters were explored visually and haptically in the first intervention, they could be only visually explored in the second. In the third intervention, the letters were explored visually but in a sequential manner. In the intervention with visual and haptic exploration the children were instructed to run their fingers along its contour of the letter in a fixed order corresponding to the way it would have been written by hand. The authors found an advantage regarding pseudo-word decoding as well as understanding and use of the alphabetic principle for the intervention group who could make a haptic experience. Bara and colleagues (2007) found similar results in an intervention study with children from low socio-economic status families. Performance in the letter recognition task and initial phoneme recognition were better after a training including a haptic experience. Furthermore, the effect of the haptic exploration manifested in better results in pseudo-word decoding in a delayed test. Likewise, Kalenine and colleagues (2011) showed that a visuo-haptic intervention – compared to a unimodal visual intervention – led to better performance in recognition of geometrical shapes in kindergarten children.

Tracing has also been investigated in multimedia research with a number of other more complex, scientific learning materials, such as temperature curves (Agostinho et al.,2015), triangle geometry (Ginns et al.; 2016, Hu et al. 2015; Yeo & Tzeng, 2020), the water cycle (Tang et al., 2019), or the function of the human heart (Ginns, & Kydd, 2019; Korbach et al., 2020; Macken, & Ginns, 2014). For example, Agostinho and colleagues (2015) investigated the effect of tracing on the interpretation of temperature curves displayed on a tablet. Students aged eight to eleven years were assigned to one of two conditions. Students in both conditions were given example tasks and information on how to read a temperature curve. While one group was then asked to use the index finger to follow relevant diagram elements, the other group was only allowed to look at the temperature curve. The authors found that those participants who used tracing performed better in a transfer test than those who merely looked at the diagrams. Ginns and colleagues (2016) found similar results in two experiments in which children were given paper-based instructions on triangle geometry (Experiment 1) and on the order of operators for arithmetic tasks (Experiment 2). Here, too, one group was asked to explore the example tasks with the index finger, whereas the other group was only allowed to look at the materials. In both experiments, participants in the tracing condition yielded better results in a transfer test than those in the control condition. In a study by Tang and colleagues (2019), it was found that primary school students who traced while studying learning material about the water cycle scored higher in recall and transfer tests than students who were not allowed to trace.

According to Fiorella and Mayer (2016) tracing can be considered as an example of learning by enacting which they describe as one technique to promote generative learning. This “involves actively making sense of to-be-learned information by mentally reorganizing and integrating it with one’s prior knowledge, thereby enabling learners to apply what they have learned to new situations” (Fiorella, & Mayer, 2016, p. 717). Learning by enacting means that task-relevant movements are integrated in the learning process and refers to theories of embodied cognition (Barsalou, 2008).

Taken together, the haptic experience of the learning material which is gained by tracing seems to positively affect learning outcomes. However, there are a few things that should be kept in mind. First, the presented studies in the field of finger tracing all deal with rather abstract learning material, such as geometrical concepts or alphabetic learning. Second, finger tracing is a guided exploration. The participants in the experiments are instructed exactly in which way and in which order they should trace the learning material with their finger. This can be contrasted with a free exploration, which may even allow the use of the whole hand or both hands. Third, in the tracing studies it is only dealt with two-dimensional, flat learning material that does not contain any spatial information, contrary to what objects or three-dimensional models are capable of providing. Accordingly, the next section gives a deeper insight into the role that real, touchable objects could play in the learning process and deals with a learning context in which real, authentic, three-dimensional objects are of great importance: the museum context (Howes, 2014). I will give a short introduction of object-based learning (OBL, Chatterjee et al., 2015; Rowe, 2002) and some insights of the role of touch in the museum.

Object-Based Learning and the Haptic Sense in the Museum

OBL attributes a special influence on the learning experience to the haptic interaction with objects. OBL is based on a multisensory, constructivist approach. On the one hand, information from different senses – especially the sense of touch – is integrated, on the other hand, it is presumed that learners evolve their knowledge and understanding specifically through the interaction with objects. The learning technique aims to enable students to explore processes and events related to the object of interest, encouraging them to link these experiences to abstract ideas and concepts (Chatterjee et al., 2015; Rowe, 2002).

There are some studies that deal with OBL – especially in a museum context. In these mostly qualitative studies, the focus lies on the special, memorable learning experience that learners get the chance to make when they are provided with the possibility to haptically interact with objects. For example, Tam (2015) conducted three case studies on OBL and showed that it can encourage student-centered learning. In the third case study, 34 students explored two sculptures and reflected on their experiences of viewing and touching them. Conclusions on students' learning experience and the impact on learning are drawn from reflective essays written by the students. The students described that touching feels more reliable than just seeing the sculptures, and that it can facilitate the understanding of the objects. Furthermore, touching can assist to correct misconceptions, for example on the weight of the objects. Overall, the haptic exploration of the objects led to a more intense learning experience that helped to build up confidence in the students' learning. Tam concludes "learning is enhanced, enriched and broadened through touching. I strongly argue that learning through touch should be included more commonly at all levels of teaching" (p. 130).

Sharp and colleagues (2015) presented evidence for the value of object-based learning from a range of disciplines, like art, zoology, and archaeology. They drew conclusions from a semi-structured questionnaire with quantitative and qualitative questions which was completed by 432 students. Specifically, these researchers discuss the nature of knowledge acquisition and the importance of providing a multisensory experience. Their study revealed that OBL can be beneficial across a range of disciplines. The findings showed that the combination of vision and the haptic sense resulted in higher engagement and improved knowledge and understanding throughout.

Importantly, there are other studies – apart from OBL – that deal with the role of haptics in museums. Christidou and Pierroux (2018) investigated touch as an interpretive resource in an art museum. Like Lederman and Klatzky (1987), they identified patterns of hand movements which they called "real" touch and that can be used as sources of information to gain knowledge on the sculptures' shape, texture, substance, and on its creation process. They found that museum visitors that could touch the sculptures "moved, viewed, described and discussed the works in more diverse ways than when viewing only, and that touch fostered longer and deeper object-related enquiries." (Christidou & Pierroux, 2018, p. 16).

Koran and colleagues (1984) compared visitor behavior in two different conditions: one group of visitors could only visually inspect objects in a museum gallery, whereas another group was allowed to touch and move the objects. The number of visitors entering the gallery increased significantly when the exhibits could be touched. The authors pointed out that "when manipulatable objects from the same exhibit are presented for inspection, permitting touch, hearing, sight, and perhaps taste and smell, curiosity is stimulated and interest appears to significantly increase […] Since a greater number of sensory channels can be activated when the stimulus can be manipulated, observers attend to the stimulus in greater numbers" (p. 361).

Additionally, there are studies that indicate that not only the haptic experience of original objects in museums is appreciated, but also the handling of three-dimensional printed replicas. In a study by Di Franco and colleagues (2015) museum visitors favored replicas over original artifacts, because of the haptic experience they could have with the replicas. They emphasized that the participants are "more concerned with experiencing an object through the senses rather than having the original in front of them" (p. 260). Wilson and colleagues (2017) found similar results: In their study, handling three-dimensional printed replicas enhanced the museum experience and visitors' understanding and enjoyment of the exhibits. Especially for blind and visually impaired visitors, touchable objects facilitate the experience of the exhibition contents. The visitors also pointed out that they would appreciate it if touchable three-dimensional printed replicas were exhibited in more museums, and that the possibility of handling them would serve as motivation for visiting more museums.

Taken together, these studies show that haptic exploration can have a positive effect on the museum visit experience and can support the understanding of and engagement with the exhibition content. However, there is still a lack of systematic, quantitative, unifying research on the influences of the haptic experience in an informal learning setting on different aspects of the learning process, as assumed in CATLM.

Benefits of Haptic Exploration

The CATLM provides different components which are relevant for learning in multimedia setting: attention and information selection, processing in working memory, storage in long-term memory, motivation, and affect. The previous discussion of finger tracing and the role of haptic exploration in the museum gave first insights on the benefits which the haptic experience can provide regarding the different components of the CATLM.

The presented museum studies (Di Franco et al., 2015; Koran et al., 1984; Wilson et al., 2017) showed that attention and selection processes can be supported by providing a haptic experience of the exhibition contents in the museum. According to the OBL approach, haptic exploration of objects can be a first step in approaching a particular topic and thus motivate learners to engage further with the topic (Chatterjee et al., 2015). This finding is also supported by learning in biochemistry courses. Here, touchable models are named as favored and most useful learning tools compared to other kinds of instructional media (Harris et al., 2009; Roberts et al., 2005). Roberts and colleagues (2005) found that the handling of touchable models stimulated students' interest in molecular structure and function. Furthermore, Dohn (2011) investigated how situational interest is evolved during a school excursion to an aquarium. Using a qualitative approach, he found that hands-on experiences – among four other variables – can generate situational interest.

The empirical research on finger tracing showed that the haptic experiences of the learning material can facilitate learning (e.g. Agostinho et al., 2015; Ginns et al.; 2016; Ginns, & Kydd, 2019; Hu et al., 2015; Macken, & Ginns, 2014; Tang et al., 2019; Yeo & Tzeng, 2020). Moreover, it has been argued that the haptic experience can support cognitive offloading, thereby reducing extraneous cognitive load and releasing working memory resources for enhanced elaboration (Manches & Malley, 2012; Pouw et al., 2014). Empirical research on finger tracing yielded mixed results regarding the positive effect of tracing on cognitive load (e.g. Agostinho et al., 2015; Ginns et al., 2016; Hu et al., 2015; Yeo and Tzeng 2019). Furthermore, Hutmacher and Kuhbander (2018) demonstrated that haptic experiences of objects produce detailed and durable long-term memory representations.

Although CATLM considers that learning in multimedia environments may influence the affective state, to the best of my knowledge, there is no systematic research on the impact of haptic experiences on affect in educational settings. However, Romanek and Lynch (2008) argued that touching an object in a museum can arouse different emotions. This is consistent with findings from other research areas, which suggest that haptic exploration can induce and intensify either positive or negative affective responses (Etzi et al., 2016; Oum et al., 2011; Peck & Childers, 2003; Peck & Shu, 2009; Peck & Wiggins, 2006; Skolnick, 2013).

In summary, it is evident that the haptic sense can support and enrich the learning experience and learning at different levels. Not only on the cognitive, but also on the motivational-affective level the haptic sense seems to enhance learning. However, there is still a lack of research combining these different levels to provide a comprehensive picture of where the haptic experience can be particularly effective. This is the point where the present thesis starts.

Dissertation Overview

Based on the presented theoretical constructs and empirical findings, this thesis examines the influence of haptic exploration of objects, like tools and artifacts, in an informal learning environment, such as museums or exhibitions. The previous discussion suggests – in line with the assumptions of the CATLM and OBL – that the haptic exploration of real objects can benefit attention and the selection of information as well as its processing in working memory. This positive impact may even extend to storage in long-term memory and to motivation to deal further with the subject matter exemplified by the objects. OBL indicates that learners develop their knowledge through the interaction with objects and that this can lead to a memorable learning experience (Chatterjee et al., 2015).

Inspired by these approaches, I was interested in the question whether the use of the haptic sense could support a holistic learning experience which is not only based on "hard" cognitive outcomes, but also on "soft" outcomes such as motivation and affect. Therefore, in the three studies, which constitute the empirical work of this thesis, I used a multi-criteria approach with a broad variety of dependent measurements. Referring to the CATLM (Moreno & Mayer, 2007), the leading hypothesis of this thesis is that the more sensory channels are used during knowledge acquisition, the more intense the engagement with the learning content should be. The involvement of multiple senses – especially the haptic sense – during learning should have an impact on information selection, motivation, affect, memory, and knowledge acquisition. Following this logic, touching objects while looking at them was expected to be better in regard of these outcomes than touching objects without vision or looking at them without touching, which in turn should be more supportive than neither seeing nor touching objects. I was questioning whether this would really be the case, or whether vision without touching would be more beneficial than touching the objects without looking at them. On the one hand, based on assumption that touch constitutes an important information channel in its own right, touching objects without vision should be as effective as looking at them without touching. On the other hand, considering the visual dominance over the haptic sense, vision without touching could be more beneficial than touching the objects without vision (Hecht, & Reiner, 2009).

Museums and exhibitions are a central source for learning in an informal learning environment – for adults, but also for children and adolescents (Bell et al., 2009; Falk et al., 2007). Falk and colleagues (2007) argue that "schools do make an important contribution to public science understanding, however most of the public's science learning is 'extra-curricular,' driven by individual needs and interests and achieved through the vehicle of free-choice learning" (p. 464). This statement emphasizes the special aspects of learning in a museum: free-choice, life-long, and self-paced. Falk and Dierking (2013) describe that "exhibitions […] allow people to see, ideally even touch, taste, feel, and hear, real things from the real world in an appropriate setting." (p.113), resulting in highly distinctive motivational, affective, and cognitive visitor experiences. In contrast to the tracing studies (e.g. Agostinho et al., 2015; Ginns et al.; 2016; Ginns, & Kydd, 2019; Hu et al., 2015; Macken, & Ginns, 2014; Tang et al., 2019; Yeo & Tzeng, 2020), which classically examine guided haptic exploration, the museum context offers an opportunity to examine a free, non-forced, and self-guided haptic exploration conducted directly and naturally by museum visitors. This "free-choice" characteristic of learning in a museum, but also the complexity of the museum learning experience itself (see contextual model of learning, Falk & Dierking, 2013), enable and require a multi-criterial approach at the same time, in which motivational-affective aspects play an essential role in addition to cognitive ones. While early museums were often institutions where the objects on display could be handled, by the nineteenth century, unfortunately, a no-touch policy for visitors was established in museums (Classen, 2005). However, the introduction of the Exploratorium by Frank Oppenheimer in 1969 supported the re-entry of haptic exploration into science centers around the world aiming to make science tangible (Allen, 2004; Ogawa et al., 2009). Nowadays, the opportunity to have physical experiences is a key feature of many science museums (Allen, 2004; Howes, 2014). Especially in museum education programs, interaction with objects is encouraged (e.g., Achiam et al., 2016).

I chose the museum context to serve as an informal learning environment for all of my studies. Therefore, I developed and designed an experimental exhibition on the topic of animal husbandry, breeding, and welfare covering, among other things, the conditions under which pigs and cattle are kept, information on processes in the dairy industry, the impact of conventional animal husbandry on the climate and the environment, and information on alternative, environmentally friendly diets. This topic is currently – also in terms of the climate crisis – highly debated in Germany and therefore attracts a high amount of interest. This is also mirrored in the fact that a new permanent exhibition on this topic is planned for 2021 at the Deutsches Museum in Munich. Furthermore, the topic is extremely valuable for investigating the influence of the haptic experience in learning. A wide range of instruments and tools are used in animal husbandry, which can assist in presenting and conveying the contents of the exhibition. Remarkably, these tools are unfamiliar to the learners, so that they arouse their curiosity to delve deeper into the topic. Moreover, their instrumental quality encourages the urge to handle and try them out. Haptic experiences can help to understand the functionalities of the tools better (Gibson, 1966, 1979). Therefore, each section of the experimental exhibition was introduced with an accompanying touchable exhibit.

In total, I conducted three studies, which are summarized in Table 1. In the next sections, I will briefly review the individual studies. For more details, the separate studies can be found in the Appendix.

Table 1

Overview of the studies

	Study 1	Study 2	Study 3
Setting	Laboratory	Laboratory	Field
Design	2 × 2 between-subjects design with the factors vision (yes/no) and haptics (yes/no)	2 × 2 between-subjects design with the factors vision (yes/no) and haptics (yes/no)	One factorial between-subjects design with the factor object display type (photo/vision/haptics and vision)
Main dependent variables	Situational interest in the first and in the second showroom Recall of the objects Knowledge acquisition Positive and negative affect after the first and the second showroom	Situational interest Recall of the objects Extended free recall Knowledge acquisition Positive and negative affect	Visit behavior Situational interest Free recall Knowledge acquisition Perceived freedom of choice Positive and negative affect
Participants	Mainly students	Mainly students	Museum visitors
Sample size	163	163	186
Follow-up	Yes ($N = 115$)	Yes ($N = 103$)	No

Study 1

The first study took place at the Leibniz-Institut für Wissensmedien in Tübingen (see Appendix B). For this study, I developed and set up the experimental exhibition in a laboratory setting. This experimental exhibition consisted of two showrooms. In the first showroom, the sensory access of the participants to the exhibition objects was systematically varied in a 2 × 2 design with the between-subjects factors vision (yes: objects visible / no: objects not visible) and haptics (yes: objects touchable / no: objects not touchable). To create a rich multimodal learning experience, all of the participants could use an audio guide to get additional information on the objects (see Figure 2).

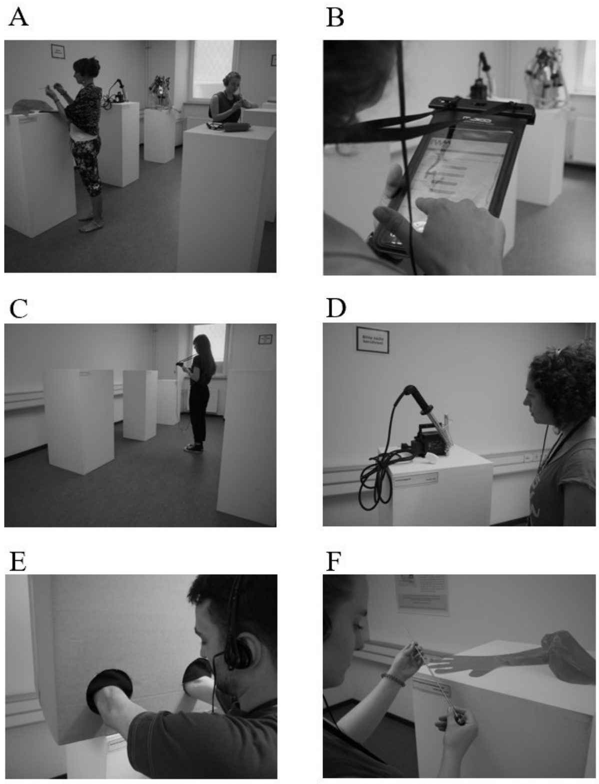

Figure 1. In the first showroom, I presented six different tools that are typically used in animal husbandry. (A) Overview of the first showroom in the vision-and-haptics condition; (B) participant using the audio guide; (C) participant in the no-objects condition; (D) participant in the only-vision condition; (E) participant in the only-haptics condition; (F) participant in the haptics-and-vision condition

In the second showroom, further information on topics related to the objects were presented using posters with texts, illustrations, and diagrams (see Figure 3). This showroom was the same for every participant. I aimed to investigate whether the haptic experience in the first showroom served as a motivator to engage further with the topic. I assumed that the more sensory channels are used during knowledge acquisition, the more intense the engagement with the learning content should be. This should have a positive effect on a variety of cognitive as well as motivational-affective outcomes and should transfer in the second showroom. The main dependent variables in this study were situational interest in the first and in the second showroom, recall of the objects, knowledge acquisition and positive and negative affect after the first and the second showroom.

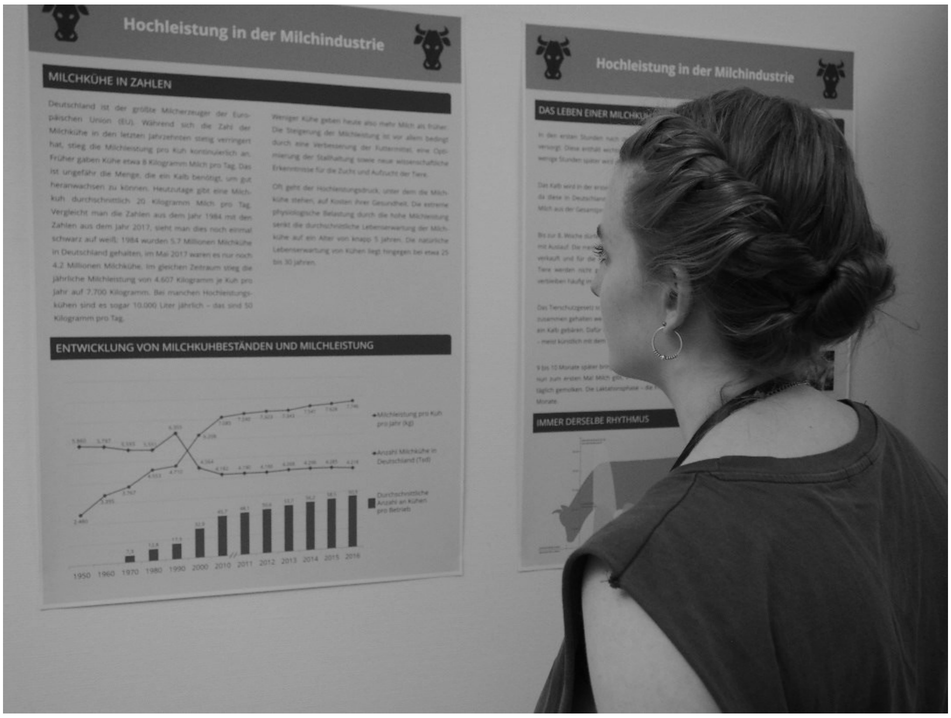

Figure 3. In the second showroom, I presented posters with further information on object-related topics. The posters included texts, illustrations, and diagrams.

A central aspect of my work is the question of how sustainable the effect of the haptic experience is. I measure this in two ways. In addition to the main investigation, I conducted a follow-up after three weeks to see if the additional haptic exploration had long-term effects on participants' memory and knowledge processes. Furthermore, the question regarding the impact of the haptic experience on the reception and processing of further, subsequently presented information was a central part of the first study. Does a haptic exploration of topic-specific objects in the first showroom lead participants to be motivated to deal with this topic more intensively subsequently in the second showroom? In other words, does such a haptic experience have a lasting effect on the participants' engagement with a topic?

The first study had a sample size of 163 participants who ranged in age between 18 and 66 years (M= 24.76, SD= 7.55); 120 of them (73.6%) were female, 42 (25.8%) were male, and one (0.6%) was diverse (non-binary).

The participants in all experimental conditions engaged intensively with the exhibition content: the first showroom was visited for an average of just under a quarter of an hour, the second showroom an average just over 20 minutes. Most of the participants engaged with almost all of the exhibited posters and objects.

Immediately after visiting the entire exhibition, participants showed a high accuracy in the recall of objects exhibited, as long as the objects were offered in the first showroom for either haptic or visual exploration, or a combination of both. Hence, there was a general benefit of the conditions in which objects were provided, compared to the condition without objects. After three weeks, participants who were allowed to use their visual and haptic senses during the exhibition remembered significantly more objects than participants who could only see or neither see nor touch the objects. There was no significant difference between the haptics- and the vision-and-haptics condition.

Furthermore, neither the knowledge test regarding the first nor regarding the second showroom revealed any advantage for the participants who were offered a haptic experience. Additionally, it was found that the haptic experience intensified the feeling of negative affect, but not the feeling of positive affect or situational interest. Overall, the results suggest that the effects of the haptic experience in the first showroom could not be transferred in the second showroom. Thus, there is no evidence that the haptic experience served as a motivator to engage further with the topic.

Study 2

According to the principle of spatial contiguity established in the CTML, students learn more effectively in a multimedia setting if words and images that belong together are introduced close to each other and not far apart (Mayer & Fiorella, 2014). Similarly, the principle of temporal contiguity states that it is beneficial for learning if matching learning materials are presented simultaneously rather than sequentially (Mayer & Fiorella, 2014). I have taken up these principles in the second study by merging the two showrooms from the first study into one showroom in order to avoid a shift in time and space (see Appendix C). Consequently, the objects were presented together with the posters in one showroom (see Figure 4).

Figure 4. Overview of the Experimental Exhibition in the Second Laboratory Study.

Like the first study, this study took place at the Leibniz-Institut für Wissensmedien in Tübingen in a laboratory setting. Again, the sensory access of the participants to the exhibition objects was systematically varied in a 2 × 2 design with the between-subjects factors vision and haptics and an audio guide that provides information on the functions of the objects to intensify the multimedia learning experience. Analogously to the first study, I hypothesized that under conditions of high spatio-temporal contiguity, the more sensory channels are used during knowledge acquisition, the more intense the engagement with the learning content should be. The main dependent variables were situational interest, recall of the objects, knowledge acquisition, and positive and negative affect. I additionally used an extended free recall as a new dependent variable ("description task"). Here, the participants were asked to name all features of the objects exhibited that they could remember. After three weeks, a follow-up study was conducted to evaluate the long-term effects of the different experimental conditions. The age of the 163 participants in this study ranged between 18 and 34 years (M = 23.63, SD = 3.00); 127 of them (77.9 %) were female, 33 (20.2 %) were male and three (1.9 %) were diverse (non-binary).

Unfortunately, the second laboratory study did not provide clear evidence that the haptic experience had a positive effect on the reception of the exhibition. As in the first study, participants in all experimental groups engaged very intensively with the contents of the exhibition. This was reflected both in long stays in the exhibition of almost half an hour on average and in the fact that most participants examined the entire exhibition content.

Regarding the recall of the objects, the results confirmed the findings from the first study. Immediately after the exhibition, there was a general advantage of those experimental groups in which the objects were available in the exhibition room. In the follow-up, especially the combination of the haptic and visual sense was beneficial for the recall. In the knowledge acquisition test, I could not find any differences between the experimental groups – neither in the main study nor in the follow-up. Thus, the haptic experience did not support the learning of additional, object-related knowledge.

The description task was analyzed separately in regard of the number of correct facts, the number of correct audiotext details, and the number of correct object details. There was no clear advantage for the participants who could have a haptic experience. On the contrary, the participants in the only-haptics-condition even mentioned less audiotext information than the participants in the other conditions.

There were no significant differences between experimental groups in positive and negative affect. However, participants with haptic experience reported a higher SI-Catch. In contrast, there were no differences in SI-Hold between the experimental groups. Even though the results on a motivational-affective level are ambiguous in both laboratory studies, the participants seem to perceive touching the exhibition objects as an impressive experience. The following quotations are examples of the responses to the question “What did you like best about the exhibition?”:

> *Das Thema interessiert mich persönlich sehr, da ich Vegetarierin bin. Besonders interessant war der Einstieg in Raum 1 mit dem Ertasten und Fühlen der Werkzeuge. Das direkte „Erleben“ ist nochmal „greifbarer“ als nur etwas zu lesen. Das anschließende Lesen der Infos in Raum 2 hat dann die Neugierde, die man in Raum 1 erlebt hat, mit Fakten und weiteren Infos befriedigen können.*
> (Participant in the only-haptics-condition, first laboratory study)
>
> *Dadurch dass man die Geräte anfassen konnte, ist dies sehr real für mich gewesen. Normalerweise entziehe ich mich gern diesem Thema und schaue weg, aber wenn man die Geräte so vor sich liegen sieht, kann man sich dem weniger entziehen und ich habe gemerkt, wie grausam das alles sein muss für die Tiere. […]*
> (Participant in the vision-and-haptics-condition, first laboratory study)
>
> *Die Kombination aus Audioguide und vor allem dem Ertasten der Nutzgeräte haben mir die Brutalität unserer Nutztierhaltung noch einmal auf eine Art und Weise bewusst gemacht, wie ich es, obwohl ich mich über dieses Thema informiert glaubte, noch nicht erlebt habe. Ich denke viele Menschen könnten über den Tastsinn zu tiefgründigeren Reflexionen angeregt werden als über bloße Plakate und Bilder.*
> (Participant in the only-haptics-condition, second laboratory study)
>
> *Die Ausstellungsobjekte zum Anfassen waren sehr eindrücklich. Gerade weil man diese nicht sehen konnte, sondern nur ertasten, hat man sich ähnlich wehrlos und ängstlich wie die Tiere gefühlt.*
> (Participant in the only-haptics-condition, second laboratory study)

These quotes from the studies represent the intensity and impressiveness that can come from a haptic exploration. Some participants became aware of the reality and significance of the subject matter through the haptic experience, which can encourage them to reflect and rethink their own behavior.

Study 3

For the first two studies, I set up an experimental exhibition in a laboratory setting. This had the advantage of a relatively high degree of controllability with few distracting factors, as I was able to control access to the exhibition properly and the participants had a separate room to fill out the questionnaires. Also, the ecological validity can be regarded as sufficient, since the participants were able to move freely in the experimental exhibitions and were allowed to explore the exhibition in their own interest and at their own pace – as if they were in a real museum. However, the museum atmosphere in a laboratory setting is missing. In addition, in both studies, the sample was mainly composed of students, who were recruited through the institute's own recruitment portal and paid for their participation. Real museum visitors certainly come to a museum with a different mindset than participants to a study. For this reason, in the third study I wanted to investigate whether the results of the first two studies can also be found under authentic museum conditions with real museum visitors. This field study had a high ecological validity but was also less controllable.

Therefore, the third study took place in the Deutsches Museum in Munich and was part of the DFG knowledge transfer project “Conveying Conflicting Scientific Topics in Exhibitions” funded by the German Research foundation (see Appendix D). For this study I used a slightly different exhibition than for the other two studies (see Figure 5). This exhibition dealt with the same topic but was less extensive than the exhibitions I used in the laboratory studies. However, the small mock-up exhibition used in the study will be part of the final permanent exhibition at the Deutsches Museum, which is scheduled to open in 2021. In the study, the between-subjects factor “object display type” was systematically varied by setting up three different versions of the mock-up exhibition. A comparison was made between (1) displaying objects photos (photo condition), (2) displaying actual objects that can be visually inspected (vision condition), and (3) displaying actual objects that can be visually and haptically explored (touch condition).

Figure 5. (A) Overview of the mock-up exhibition in the photo condition; (B) pig toy in the photo condition; (C) castration forceps in the vision condition, and (D) dehorning device in the touch condition.

Again, I used a multi-criteria approach with the main dependent variables visit behavior, free recall, knowledge acquisition, perceived autonomy, situational interest, and positive and negative affect. The main research question was how different (sensory) approaches to authentic objects affect the cognitive and motivational-affective characteristics of museum visitors.

The participants of this study were 186 museum visitors of the Deutsches Museum in Munich. They ranged in age between 18 and 79 years (M = 35.15, SD = 14.14) and 82 of them (44.1%) were female. Similar to the laboratory studies, there were no significant differences between the experimental groups in the duration of stay or in the intensity of engagement with the exhibition content.

It was found that the participants who were allowed to touch the objects remembered significant more objects and accompanying exhibition topics in a free recall and perceived higher autonomy than participants in the other two conditions. Unexpectedly, participants in the photo condition reported higher values for situational interest as well as for positive and negative affect compared to participants in the other two conditions. There were no significant differences between the experimental groups in the knowledge acquisition test. The participants in this field study were also asked in an open-ended question what they liked most about the exhibition. Of those participants who had a haptic experience 40 % stated that this experience was the best thing about the exhibition.

General Discussion

Summary and Discussion of Findings

The results of the three studies that form the empirical basis of this thesis are described in more detail in the publications in the appendix. In the following, the results of the studies are summarized and discussed with regard to the different dependent variables.

Visit Behavior / Information Selection

In all three studies, I examined participants' visit behavior and their way to select information. No differences between the experimental groups were observed according to these outcome variables across the studies. Thus, the conducted studies do not provide evidence that haptic exploration influences visit behavior with regard to the duration of stay or the selection of and engagement with exhibition content. However, when interpreting the results, it is important to note that all subjects in all three studies – regardless of the experimental group – explored the exhibition content very intensively. This could be due to the fact that the exhibition subject affects everyone and is extremely topical. In addition, it was a relatively small experimental exhibition and not a large exhibition area where museum visitors have a wide choice of exhibition content and may have to select which objects they want to explore and which objects to skip. For further research, it is therefore interesting to investigate how the possibility to haptically experience objects affects visit behavior in a larger exhibition area with more objects. Here, it would be possible to offer objects that may be touched and to prohibit others from being touched. In this way, one could investigate whether the touchable objects attract more attention and are more likely to be selected for engagement.

Cognitive Outcomes

Regarding cognitive outcomes, the question arises to what extent haptics can influence learning and memory in my studies. First, participants acquire declarative knowledge about the concrete objects themselves. According to my hypotheses, this knowledge could be intensified by the haptic experience, since it enables participants to feel the material properties and to hold and actually “try out” the tool. This also leads to the assumption that the haptic experience can positively influence procedural knowledge, as the participant gets a direct impression of how the tool has to be handled and thus better understands the functions that are explained by the accompanied texts and audio recordings. Lastly, I aimed to investigate the question whether the haptic experience leads to stronger memory links being made to further information, i.e., the enhancement of factual knowledge. In my studies, I used different instruments to measure cognitive outcomes: free recall and recall of objects, respectively, knowledge acquisition tests and an extended free recall (“description task”) in the second laboratory study.

In both laboratory studies, I observed an advantage for those conditions in which objects were presented – regardless of whether they were allowed to be explored haptically or not – over the condition in which no objects were exhibited at all regarding the recall of objects immediately after the exhibition. However, the follow-up after three weeks showed that especially the combination of the visual and haptic sensory channel led to a stronger mental representation of the exhibited objects. A slightly modified form of free recall was used in the field study. Here, the participants were asked to name not only the presented objects, but also the exhibition contents that were associated with them. The participants were thus challenged to establish a connection between the exhibited objects and the exhibition texts presented. Compared to the participants in the other two experimental groups, the participants who were allowed to explore the objects haptically were able to remember a larger number of objects and exhibition contents. In addition, it was shown that looking at the objects also had beneficial effects on memory performance compared with the presentation of the photos of the objects. The results of the free recalls suggest on the one hand that haptics support encoding and retrieval of the presented objects. On the other hand, the results of the field study offer initial indications that haptics can facilitate connections between objects in an exhibition and further exhibition content. Still, when considering the results in the knowledge acquisition tests in all three studies, there are no indications that participants who were allowed to haptically explore objects had built up deeper factual knowledge on the exhibition content than the participants who were not allowed to touch any objects.

In the second laboratory study, participants were additionally asked to list all the features of the presented objects that they could remember. Here, three different response categories were examined: the number of correct facts, the number of correct audiotext details and the number of correct object details. Overall, the participants who had not seen or touched any objects at all listed fewer facts about the objects than the participants in the other groups. Data analyses also revealed that in the condition in which there was a haptic exploration without visual input, the smallest amount of information was extracted from the audiotext. This was true for both the main investigation and the follow-up. Perhaps participants in this condition were so focused on the haptic exploration that they did not listen as carefully to the audiotexts as participants in the other conditions. Alternatively, the haptic and object-related perceptions may have been so impressive that these were more likely to be recalled during retrieval. When interpreting the results, it should be kept in mind that this was an open-ended response format and the participants were not asked to reproduce the information from the audio texts.

In summary, with regard to cognitive outcomes, it was found that haptic exploration especially influences object-related, declarative knowledge in a positive way. There is no clear evidence that the haptic experience has a beneficial effect on procedural knowledge or supports the linking with further, factual knowledge. There is a need for further research here to verify the present findings using other learning topics and learning settings. Regarding cognitive outcomes, other test formats should be considered in particular. In the present studies, it is arguable whether the mixture of open formats and closed formats was appropriate to properly represent what participants had actually learned. In subsequent studies, one could, for example, film the participants using the tools to explain how to apply them in practice. The video recordings could then be evaluated for correctness and level of detail. In this way, it would be possible to determine whether the haptic experience promotes procedural knowledge. Personal Meaning Mapping (PMM, e.g. Hartmeyer et al., 2017; Falk et al., 1998) would also be a good method to find out to what extent the reception of an exhibition leads to a broader, more complex knowledge about a topic and whether the haptic experience supports this. Additional ideas for further research are presented and discussed in the section "Outlook and Future Directions".

Motivational-affective Outcomes

With regard to motivational-affective outcomes, a mixed, ambiguous pattern of results emerged. One of the main questions of the first study was whether the haptic exploration in the first showroom could serve as a motivator to further engage with the topic in the second showroom. No evidence for this assumption was observed – no differences between the experimental groups in the second showroom were detected.

In all three studies, the situational interest of the participants was recorded. While the first study showed no differences between the experimental groups, in the second study I observed a difference between groups regarding the catch component of situational interest. This indicates that the haptic experience helps to catch the attention of the participants and supports them to initially engage with the topic of the exhibition. No differences were found regarding the hold component of situational interest. Surprisingly, in the field study, participants in the photo condition reported higher situational interest than participants in the touch condition. Interestingly, situational interest was high in both laboratory studies, even in the no-objects-condition. This suggests that the exhibition itself, with its topical content, arouses the participants' interest. Also, it is conceivable that the absence of the objects builds up a certain curiosity regarding these objects, which is reflected in the responses of the situational interest questionnaire.

The results were also inconclusive with regard to affect. I would have expected that, touching the objects would intensify either negative affect due to the rather negative nature of the objects or increase positive affect due to the possibility of handling non-commonplace objects, or both. While the haptic experience had an effect on negative affect in the first study, this could not be confirmed in the other studies. Here, there were either no differences between the experimental groups or more positive affect was reported by the participants in the photo condition in the field study.

Since a main quality of the museum in general is its free-choice learning character, the perceived autonomy was investigated in the field study. This revealed that the participants with haptic experience perceived more autonomy than the other participants, even though it was a small experimental exhibition. This suggests that the haptic experience may foster an important prerequisite for experiencing intrinsic motivation.

Considering the open-ended question of what the participants liked best about the exhibition, the answers in all three studies indicate that the haptic experience was really impressive and valued by the participants. However, this does not seem to be fully captured by the questionnaire instruments used. Therefore, alternatives for measuring motivation and affect should be considered in subsequent studies. One could imagine asking the participants directly what feelings the visit of the exhibition and especially the haptic exploration triggered in them. The use of objective measures (e.g. psychophysiological measurements) could also be considered, as these cannot be biased by social desirability effects.

Theoretical and Practical Implications

Even though the results of the present studies provide mixed results on different levels of learning and learning experience, certain implications can be drawn regarding existing multimedia learning theories and the practical use of touchable objects as instructional media.

CATLM only considers narratives, sounds, texts, and pictures as media for instruction. Three-dimensional objects, such as tools, as an additional type of learning media are not mentioned. However, the studies of this thesis show that the provision of tools that illustrate the learning topic does have a positive effect on the retention of the learning content – regardless of whether haptic exploration is permitted or not. Other studies indicate that this is not only true for real objects, but also for three dimensional models, such as those that can be created through 3D printing (Smith, 2016; Stull et al., 2018). This is an important finding, especially for curators and designers in museums and exhibitions, as a lot of time and money is usually invested in the acquisition, selection and arrangement of the exhibits. This investment seems to be worthwhile in terms of the museum visit experience.

Previous research and most multimedia learning theories have focused on the auditory and visual senses. The central aim of my work was to explore whether the haptic sense is an additional channel to support and enhance the learning process. While previous research has mainly dealt with abstract learning material, such as finger-tracing of pictorial learning material (e.g. Agostinho et al., 2015) or manual interaction with three-dimensional molecular models (Stull et al., 2018), my research focused on the handling of real objects respectively tools. Following this existing research, an advantage of the (additional) haptic channel was found in the retrieval of the tools. Consequently, an addition of the haptic channel to multimedia learning theories should be considered. However, free exploration of the tools – contrary to the assumptions of OBL – did not lead to better performance in the knowledge acquisition tests that asked for factual knowledge. In my studies, the link between the learning content and the haptic exploration may not have been strong enough. For example, in the research on tracing, it is the case that there is a predetermined, guided haptic exploration that has a clear, meaningful connection to the learning material. This should also be considered in future studies that investigate the role of touching and exploring three-dimensional objects, such as tools and artefacts, on different learning processes. The haptic experience should be directly linked to the learning content, e.g., by trying explained functions of a tool or by providing information about features that can only be explored haptically. Furthermore, conclusions can be drawn for the practical application of touchable objects in formal and informal learning settings. Teachers should pay attention to a meaningful integration into the learning content when using such objects. In addition, attention should be given to how to instruct meaningful exploration so that students are made aware and encouraged to directly explore certain properties and functions. Despite the still partly prevalent no-touch policy, the present study shows that the haptic experience can be useful in museums. In this context, too, it seems to be important that the exhibition texts and the explorable objects are coordinated in such a way that the properties and functions mentioned in the exhibition text can be experienced directly on the object through its handling. In this way, the exhibition text becomes more explicit through the haptic experience and understanding as well as learning is supported. These practical suggestions should be confirmed in further studies.

Some previous studies – especially studies from the museum context – showed that the additional access to educational content via the haptic channel can act on different levels. Specifically, haptics impact not only the cognitive level but also the motivational-affective level (e.g., Di Franco et al., 2015; Dohn, 2011). Thus, one aim of this thesis was to investigate to what extent haptic exploration can lead to a more holistic learning experience. Does the haptic experience affect the different levels of CATLM? Here, the three studies provided mixed results

– both on the cognitive and motivational-affective levels. In fact, indicative evidence for a detrimental effect of haptics was observed in some cases. Specifically, in the field study, participants with haptic experience reported lower situational interest and positive affect than participants in the photo condition. In the second laboratory study, participants who had solely a haptic experience of the exhibit objects provided the least amount of information from the audio text. Possibly, the haptic exploration acts as a kind of seductive detail that distracts from the audio texts (Harp & Mayer, 1997, 1998). Further studies are needed to get a clearer picture of the effects of haptic exploration. Here, the important questions to be asked are in which cases the haptic experience can have positive effects, when it is distracting or disruptive, and exactly which learning outcomes are positively or negatively influenced by it. This should also include reconsidering which instruments are used. As explained in the sections before, the use of other, possibly qualitative instruments could provide an even deeper insight into how exactly the haptic experience influences learning outcomes and the learning experience.

Strengths

The present thesis focuses on a sensory channel that has received far less attention in multimedia learning research than the visual and auditory senses: the haptic sense and its impact on learning and learning experience. The attempt to close, or at least reduce, this research gap is a clear strength of the present thesis. I extend the research literature, first by using a multi-criteria approach in which I consider affective and motivational variables in addition to cognitive variables, and second by using real, three-dimensional objects that can be explored haptically instead of two-dimensional, flat learning material or three-dimensional (molecular) models. Also, in regard of the learning setting, I chose a field that is far less researched than formal education: The museum as an informal learning environment serves as the learning setting in my studies.

Furthermore, this thesis combines research in the laboratory with a field study. This gave me the opportunity to investigate whether the results I found in the experimental exhibitions in the laboratory could also be detected in an authentic museum setting in the Deutsches Museum. Through this combination of laboratory and field studies, the empirical work of this thesis achieved a high degree of ecological validity – especially in the field study – while maintaining acceptable controllability in the laboratory studies. Additionally, the results of the studies are relevant to both theory and practice.

Although it was very important for me that the participants in my studies could have an authentic museum experience, at the same time I placed great emphasis on following scientific standards. Thus, I realized a clear, experimental design and controlled for the participants' prior knowledge and prior interest in all my studies. In my laboratory studies, I used a full 2 × 2 between-participants design in which vision and haptics were manipulated independently. In contrast to previous research, in which the haptic experience often supplemented the visual input, I was able to investigate a haptic-specific effect by implementing the only-haptics condition. In addition, I used well established measurement methods and – even if this is sometimes difficult in the museum – made sure that the experimental procedure was standardized. By using a similar methodological approach, similar designs and similar dependent variables in all studies, a good comparability between the studies is possible.

Limitations

There are several limitations of the studies in this thesis suggesting that additional research is still needed to further investigate the influence of haptics on different levels of the learning process. First, the learning topic of all my studies is animal husbandry. This topic is contemporary and important as the acquisition of knowledge about sustainable food production and animal welfare is of increasing importance in regard to climate change. Along with this, however, the tools used are not neutral objects. They can trigger disgust, rejection, as well as interest and curiosity. The results show that the confrontation with this topic and these tools can provoke different reactions in the participants. In terms of the generalizability of the present findings, it will therefore be necessary to investigate the effects of haptic exploration in the context of a more neutral, less emotional topic.

The question of generalizability also arises in regard to the chosen learning environment. It was a clear aim of my work to investigate the effect of haptic exploration in the informal learning context, as this is still far less researched than the field of formal education. Moreover, I wanted to achieve a high ecological validity with the design of my studies. It is clear, however, that one cannot achieve as high a level of controllability as in a normal laboratory study in the setting of a museum or an experimental exhibition. The participants in my studies had to have the opportunity to move around in the showrooms completely freely at their own pace and according to their own interests and to select those learning contents they really want to engage with. From a scientific perspective, this lack of guidance of the participants can have a negative effect on the quality of the data. The question therefore is whether the results can be transferred to other, more controlled learning situations.

Second, a few methodological problems should be considered. As it is often the case in studies with a follow-up, not all participants in my two laboratory studies attended the second part of the study. Especially in the second laboratory study, the dropout rate was high and unevenly distributed among the four experimental groups. This can lead to biases in the results. In addition, I used subjective measures (questionnaires) to record the motivational-affective outcomes, which are sensitive to social desirability effects. Furthermore, in my studies, I made the conscious decision not to observe or videotape the participants during their reception of the exhibition. The participants were intended to gain a museum experience as authentic as possible, which should not be disturbed by observation. Instead, I asked the participants directly after their visit to the exhibition how they had behaved in the exhibition. Additionally, it should be explicitly mentioned here that in my studies it was a voluntary offer for haptic exploration – no participant was forced to handle the tools and explore them. Although those participants who did not explore in the haptic conditions were excluded, the manner of haptic exploration may still differ greatly between participants. Of course, in future studies it would be interesting to investigate how exactly the visual and especially the haptic exploration took place. Were there specific, consistent patterns of exploration? How extensively were the different tools explored? Thinking of the exploratory procedures identified by Lederman and Klatzky (1987, 2009), such as following the contour to obtain details about shape and volume, it would be very interesting to analyze how exactly haptic exploration is used during the free reception of a showroom when the objects are allowed to be touched.

Finally, as I mentioned before, in my studies the connection between the learning content and the haptic exploration might be too weak. Referring to the OBL, I had assumed that merely the free exploration of the tools has a positive effect on the learning of object-related, factual knowledge. However, this could not be proven in the knowledge acquisition tests. In future studies, therefore, the inherit connection between the haptic exploration and the learning content should be more pronounced – as it is the case, for example, in the tracing studies.

Outlook and Future Directions

The (mixed) results as well as the limitations of the present thesis provide plenty of indications for further research on the influence of haptics on learning. In this section, I would like to give an outlook on the research questions that in my view should be addressed in the future to gain a clearer picture of the role of haptics in learning.

Starting with the museum context, it would be important and useful to investigate the role of haptics in a larger exhibition with more opportunities for selection. Here, one could provide both exhibition objects that can be explored haptically and those that may only be looked at. Will the objects that can be touched receive more attention? Also, a variation of objects that are associated with positive or negative emotions would be interesting. Are positive objects more likely to be touched than negative ones? Does the manner and intensity of exploration differ depending on the emotions triggered? Another interesting question regarding the type of objects to be explored is the question of the originality or authenticity of the object. According to previous research, authenticity plays an important role in the evaluation of objects: Authentic objects are perceived as more valuable and arouse a higher desire to keep, own or touch them (Frazier et al., 2009). Considering this connection between the evaluation and authenticity of objects, it would be intriguing to investigate whether there is a difference in terms of the intensity of exploration, but also in terms of information processing depending on whether an authentic or non-authentic object is haptically explored. This is a particularly relevant question considering that 3D printing makes it easy to produce replicas of objects.

Based on the tracing studies, it would be interesting to see whether the findings can be replicated not only in two-dimensional space but also in three-dimensional space. For this, it would be important to draw a clearer connection between the learning content and the haptic experience – as it was the case in the tracing studies, but not in my studies. The question would be whether the positive tracing effect on learning outcomes is also found in three-dimensional space, e.g., in guided exploration of anatomical models or tools.

In future research it would also be interesting to include the different exploratory procedures found by Lederman and Klatzky (1987, 2009). One could try to guide participants to use their haptic sense more purposefully through these procedures in order to benefit from the haptic experience. In this way, the potential that haptics might have in learning could possibly be better exploited than it is in free exploration. Conversely, it would be equally interesting to see whether an analysis of the exploration patterns that emerge during free exploration would reveal the procedures postulated by Klatzky and Lederman.

Conclusion

The aim of the present work was to bring one of the "forgotten" sensory channels into focus: The haptic sense and its influence on the learning experience and learning outcomes. This work was guided by the hypothesis that the more sensory channels are used during knowledge acquisition, the more intense the engagement with the learning content should be. This should affect the learning process in a variety of ways. For this I chose a multi-criteria approach using the museum as an informal learning setting. The three studies that form the empirical foundation of my work showed that making a haptic experience through touching objects can influence what we remember and how we feel. Unfortunately, there was no evidence that haptic exploration served as a motivator to further engage with a topic. However, the haptic experience did support retrieval of the exhibited objects, especially in the follow-up after three weeks. Although the results of the studies are mixed and more research is needed, this thesis constitutes a first step to fill the research gap regarding the haptic sense in multimedia learning research.

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The period as a PhD student doesn’t just offer a wonderful opportunity to deal with a scientific topic in depth, it also is a journey filled with ups and downs, and a great impetus for personal growth. For me, these were very exciting years – both professionally and privately – which I thankfully did not have to master all by myself. Throughout this time, I had some amazing people by my side who supported and encouraged me, and whom I would like to thank.

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DANKE!

References

Achiam, M., Simony, L., & Lindow, B. E. K. (2016). Objects prompt authentic scientific activities among learners in a museum programme. *International Journal of Science Education*, *38*(6), 1012–1035. https://doi.org/10.1080/09500693.2016.1178869

Afonso, A. S., & Gilbert, J. K. (2007). Educational value of different types of exhibits in an interactive science and technology center. *Science Education*, *91*(6), 967–987. https://doi.org/10.1002/sce.20220

Agostinho, S., Tindall-Ford, S., Ginns, P., Howard, S. J., Leahy, W., & Paas, F. (2015). Giving learning a helping hand: Finger tracing of temperature graphs on an iPad. *Educational Psychology Review*, *27*(3), 427–443. https://doi.org/10.1007/s10648-015-9315-5

Allen, S. (2004). Designs for learning: Studying science museum exhibits that do more than enter- tain. *Science Education*, *88*(S1), S17–S33. https://doi.org/10.1002/sce.20016

Baddeley, A. (1992). Working memory. *Science*, *255*(5044), 556–559. https://doi.org/10.1126/science.1736359

Bara, F., Gentaz, E., Colé, P., & Sprenger-Charolles, L. (2004). The visuo-haptic and haptic exploration of letters increases the kindergarten-children's understanding of the alphabetic principle. *Cognitive Development*, *19*(3), 433–449. https://doi.org/10.1016/j.cogdev.2004.05.003

Bara, F., Gentaz, E., & Cole, P. (2007). Haptics in learning to read with children from low socio-economic status families. *British Journal of Psychology*, *25*, 643–663. https://doi.org/10.1348/026151007X186643

Barsalou, L. W. (2008). Grounded Cognition. *Annual Review of Psychology*, *59*(1), 617–645. https://doi.org/10.1146/annurev.psych.59.103006.093639

Bell, P., Lewenstein, B., Shouse, A. W., & Feder, M. A. (2009). *Learning science in informal environments: People, places, and pursuits*. National Academies Press.

Chan, M. S., & Black, J. B. (2006). Direct-manipulation animation: Incorporating the haptic channel in the learning process to support middle school students in science learning and mental model acquisition. *Proceedings of the 7th International Conference of Learning Sciences*, 64–70: LEA.

Chatterjee, H. J., Hannan, L., & Thomson, L. (2015). An Introduction to object-based learning and multisensory engagement. In H. J. Chatterjee & L. Hannan (Eds.), *Engaging the senses: Object-based learning in higher education* (pp. 1-18). Routledge.

Christidou, D., & Pierroux, P. (2019). Art, touch and meaning making: An analysis of multisensory interpretation in the museum. *Museum Management and Curatorship*, *34*(1), 96–115. https:// doi.org/10.1080/09647775.2018.1516561

Classen, C. (2005). Touch in the museum. In C. Classen (Ed.), *The book of touch* (pp. 275-286). Berg

Di Franco, P. D. G., Camporesi, C., Galeazzi, F., & Kallmann, M. (2015). 3D printing and immersive visualization for improved perception of ancient artifacts. *Presence: Teleoperators and Virtual Environments*, *24*(3), 243–265. https://doi.org/10.1162/PRES

Dohn, N. B. (2011). Situational interest of high school students who visit an aquarium. *Science Education*, *95*(2), 337–357. https://doi.org/10.1002/sce.20425

Etzi, R., Spence, C., Zampini, M., & Gallace, A. (2016). When sandpaper is 'Kiki'and satin is 'Bouba': An exploration of the associations between words, emotional states, and the tactile attributes of everyday materials. *Multisensory Research*, *29*(1–3), 133–155. https://doi.org/10.1163/22134808-00002497

Falk, J. H., & Dierking, L. D. (2013). *The museum experience revisited*. Left Coast Press.

Falk, J. H., Moussouri, T., & Coulson, D. (1998). The effect of visitors' agendas on museum learning. *Curator: The Museum Journal*, *41*(2), 107–120.

Falk, J. H., Storksdieck, M., & Dierking, L. D. (2007). Investigating public science interest and understanding: Evidence for the importance of free-choice learning. *Public Understanding of Science*, *16*(4), 455–469. https://doi.org/10.1177/0963662506064240

Field, T. (2003). *Touch*. MIT Press.

Fiorella, L., & Mayer, R. E. (2016). Eight ways to promote generative learning. *Educational Psychology Review*, *28*(4), 717–741. https://doi.org/10.1007/s10648-015-9348-9

Frazier, B.N., Gelman, S.A., Wilson, A., & Hood, B. (2009). Picasso paintings, moon rocks, and hand-written Beatles lyrics: Adults' evaluations of authentic objects. *Journal of Cognition and Culture*, *9*, 1–14. https://doi.org/10.1163/156853709X414601

Gallace, A., & Spence, C. (2009). The cognitive and neural correlates of tactile memory. *Psychological Bulletin*, *135*(3), 380–406. https://doi.org/10.1037/a0015325

Geary, D. C. (2008). An evolutionarily informed education science. *Educational Psychologist*, *43*(4), 179–195. https://doi.org/10.1080/00461520802392133

Gibson, J. J. (1962). Observations on active touch. *Psychological Review*, *69*(6), 477–491. https://doi.org/10.1037/h0046962

Gibson, J. J. (1966). *The senses considered as perceptual systems*. Houghton Mifflin

Gibson, J. J. (1979). *The ecological approach to visual perception*. Houghton Mifflin.

Ginns, P. (2005). Meta-analysis of the modality effect. *Learning and Instruction*, *15*(4), 313–331. https://doi.org/10.1016/j.learninstruc.2005.07.001

Ginns, P., Hu, F. T., Byrne, E., & Bobis, J. (2016). Learning by tracing worked examples. *Applied Cognitive Psychology*, *30*(2), 160–169. https://doi.org/10.1002/acp.3171

Ginns, P., & Kydd, A. (2019). Learning human physiology by pointing and tracing. In S. Tindall-Ford, S. Agostinho, & J. Sweller (Eds.), *Advances in Cognitive Load Theory: Rethinking Teaching*. Routledge.

Harp, S. F., & Mayer, R. E. (1997). The role of interest in learning from scientific text and illustrations: On the distinction between emotional interest and cognitive interest. *Journal of Educational Psychology*, *89*(1), 92–102. https://doi.org/10.1037/0022-0663.89.1.92

Harp, S. F., & Mayer, R. E. (1998). How seductive details do their damage: A theory of cognitive interest in science learning. *Journal of Educational Psychology*, *90*(3), 414–434. https://doi.org/10.1037/0022-0663.90.3.414

Harris, M. A., Peck, R. F., Colton, S., Morris, J., Neto, E. C., & Kallio, J. (2009). A combination of hand-held models and computer imaging programs helps students answer oral questions about molecular structure and function: A controlled investigation of student learning. *CBE - Life Sciences Education*, *8(*1*)*, 29–43. https://doi.org/10.1187/cbe.08-07-0039

Hartmeyer, R., Bølling, M., & Bentsen, P. (2017). Approaching multidimensional forms of knowledge through Personal Meaning Mapping in science integrating teaching outside the classroom. *Instructional Science*, *45*(6), 737–750. https://doi.org/10.1007/s11251-017-9423-3

Hecht, D., & Reiner, M. (2009). Sensory dominance in combinations of audio, visual and haptic stimuli. *Experimental Brain Research*, *193*, 307–314. https://doi.org/10.1007/s00221- 008-1626-z

Howes, D. (2014). Introduction to sensory museology. *The Senses and Society*, *9*(3), 259–267. https://doi.org/10.2752/174589314X14023847039917

Hu, F. T., Ginns, P., & Bobis, J. (2015). Getting the point: Tracing worked examples enhances learning. *Learning and Instruction*, *35*, 85–93. https://doi.org/10.1016/j.learninstruc.2014.10.002

Hutmacher, F., & Kuhbandner, C. (2018). Long-term memory for haptically explored objects:

fidelity, durability, incidental encoding, and cross-modal transfer. *Psychological Science*, *29*(12), 2031–2038. https://doi.org/10.1177/0956797618803644

Hutmacher, F. (2019). Why is there so much more research on vision than on any other sensory modality? *Frontiers in Psychology*, *10,* 1–12. https://doi.org/10.3389/fpsyg.2019.02246

Kalenine, S., Pinet, L., & Gentaz, E. (2011). The visual and visuo-haptic exploration of geometrical shapes increases their recognition in preschoolers. *International Journal of Behavioral Development*, *35*(1), 18–26. https://doi.org/10.1177/0165025410367443

Kalyuga, S., Ayres, P., Chandler, P., & Sweller, J. (2003). The expertise reversal effect. *Educational Psychologis*t, *38*, 23–31.

Klein-Landeck, M., & Puetz, T. (2019). *Montessori-Pädagogik: Einführung in Theorie und Praxis*. Herder

Korbach, A., Ginns, P., Brünken, R., & Park, B. (2020). Should learners use their hands for learning? Results from an eye-tracking study. *Journal of Computer Assisted Learning*, *36*(1), 102–113. https://doi.org/10.1111/jcal.12396

Koran, J. J., Morrison, L., Lehman, J. R, Koran, M. L, & Gandara, L. (1984). Attention and curiosity in museums. *Journal of Research in Science Teaching*, *21*(4), 357–363. https://doi.org/10.1002/tea.3660210403

Lederman, S. J., & Klatzky, R. L. (1987). Hand movements: A window into haptic object recognition. *Cognitive Psychology*, *19*(3), 342–368. https://doi.org/10.1016/0010-0285(87)90008-9

Lederman, S. J., & Klatzky, R. L. (2009). Haptic perception: A tutorial. *Attention, Perception, & Psychophysics*, *71*(7), 1439–1459. https://doi.org/10.3758/APP.71.7.1439

Lillard, A. S. (2018). Rethinking education: Montessori's approach. *Current Directions in Psychological Science*, *27*(6), 395–400. https://doi.org/10.1177/0963721418769878

Loomis, J. M., & Lederman, S. J. (1986). Tactual perception. In K. R. Boff, L. Kaufman & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. II Cognitive processes and performance* (pp. 31.1–31.41). Wiley.

Macken, L., & Ginns, P. (2014). Pointing and tracing gestures may enhance anatomy and physiology learning. *Medical Teacher*, *36*(7), 596–601. https://doi.org/10.3109/0142159X.2014.899684

Manches, A., & Malley, C. O. (2012). Tangibles for learning: A representational analysis of physical manipulation. *Personal and Ubiquitous Computing*, *16*(4), 405–419. https://doi.org/10.1007/s00779-011-0406-0

Mayer, R. E. (2014). Cognitive theory of multimedia mearning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 43-71). Cambridge University Press.

Mayer, R. E., & Moreno, R. (2003). Nine ways to reduce cognitive load in multimedia learning. *Educational Psychologist*, *38*(1), 43–52. https://doi.org/10.1207/S15326985EP3801_6

Mayer, R. E., & Fiorella, L. (2014). Principles for reducing extraneous processing in multimedia learning: Coherence, signaling, redundancy, spatial contiguity, and temporal contiguity principles. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 279-315). Cambridge University Press.

McGuinness, C. (1990). Talking about thinking: The role of metacognition in teaching thinking. In K. Gilhooly, M. Deane & G. Erdos (Eds.), *Lines of Thinking* (vol. 2, pp. 310-312). Academic.

Montessori, M. (1912). *The Montessori method.* William Heinemann.

Minogue, J., & Jones, M. G. (2006). Haptics in education: Exploring an untapped sensory modality. *Review of Educational Research*, *76*(3), 317–348. https://doi.org/10.3102/00346543076003317

Moreno, R., & Mayer, R. (2007). Interactive multimodal learning environments. *Educational Psychology Review*, *19*(3), 309–326. https://doi.org/10.1007/s10648-007-9047-2

Ogawa, R. T., Loomis, M., & Crain, R. (2009). Institutional history ofan interactive science center: The founding and development of the exploratorium. *Science Education*, *93*(2), 269–292. https://doi.org/10.1002/sce.20299

Oum, R. E., Lieberman, D., & Aylward, A. (2011). A feel for disgust: Tactile cues to pathogen presence. *Cognition and Emotion*, *25*(4), 717–725. https://doi.org/10.1080/02699931.2010.496997

Paas, F., & Sweller, J. (2012). An evolutionary upgrade of cognitive load theory: Using the human motor system and collaboration to support the learning of complex cognitive tasks. *Educational Psychology Review*, *24*(1), 27–45. https://doi.org/10.1007/s10648-011-9179-2

Paas, F. & Sweller, J. (2014). Implications of cognitive load theory for multimedia learning. In R. E. Mayer (Ed.), *The Cambridge Handbook of Multimedia Learning* (pp. 27-42). Cambridge University Press.

Paivio, A. (1986). *Mental representations: A dual coding approach*. Oxford University Press.

Peck, J., & Childers, T. L. (2003). Individual differences in haptic information processing: The “need for touch” scale. *Journal of Consumer Research*, *30*(3), 430–442. https://doi.org/10.1086/378619

Peck, J., & Shu, S. B. (2009). The effect of mere touch on perceived ownership. *Journal of Consumer Research*, *36*(3), 434–447. https://doi.org/10.1086/598614

Peck, J., & Wiggins, J. (2006). It just feels good: Customers’ affective response to touch and its influence on persuasion. *Journal of Marketing*, *70*(4), 56–69. https://doi.org/10.1509/jmkg.70.4.056

Pintrich, P. R. (2003). Motivation and classroom learning. In W. M. Reynolds & G. E. Miller (Ed.), *Handbook of Psychology: Educational Psychology* (pp. 103-122). Wiley.

Pouw, W. T. J. L., Gog, T. Van, & Paas, F. (2014). An embedded and embodied cognition review of instructional manipulatives. *Educational Psychology Review*, *26*(1), 51–72. https://doi.org/10.1007/s10648-014-9255-5

Roberts, J. R., Hagedorn, E., Dillenburg, P., Patrick, M., & Herman, T. (2005). Physical models enhance molecular three-dimensional literacy in an introductory biochemistry course. *Biochemistry and Molecular Biology Education*, *33*(2), 105–110. https://doi.org/10.1002/bmb.2005.494033022426

Romanek, D., & Lynch, B. (2008). Touch and value of object handling: Final conclusions for a new sensory museology. In H. J. Chatterjee (Ed.), *Touch in museums: Policy and practice in object handling* (pp. 275-286). Berg.

Rowe, S. (2002). The role of objects in active, distributed meaning-making. In S.G. Paris (Ed.), *Perspectives on object-centered learning in museums* (pp. 19-36). Routledge.

Schnotz, W. (2014). An integrated model of text and picture comprehension. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 72-103). Cambridge University Press.

Sharp A., Thomson L., Chatterjee J., & Hannan, L. (2015). The value of object-based learning within and between higher education disciplines. In H. J. Chatterjee & L. Hannan (Eds.), *Engaging the senses: Object-based learning in higher education* (pp. 97-116). Routledge.

Skolnick, A. J. (2013). Gender differences when touching something gross: Unpleasant? No. Disgusting? Yes!. *The Journal of General Psychology*, *140*(2), 144–157. https://doi.org/10.1080/00221309.2013.781989

Skydsgaard, M. A., Møller Andersen, H., & King, H. (2016). Designing museum exhibits that facilitate visitor reflection and discussion. *Museum Management and Curatorship*, *31*(1), 48–68. https://doi.org/10.1080/09647775.2015.1117237

Smith, D. P. (2016). Active learning in the lecture theatre using 3D printed objects. *F1000Research*, *5*(61), 1–8. https://doi.org/10.12688/f1000research.7632.1

Smith, L., & Gasser, M. (2005). The development of embodied cognition: Six lessons from babies. *Artificial Life*, *11*(1/2), 13–29. https://doi.org/10.1162/1064546053278973

Stull, A. T., Gainer, M. J., & Hegarty, M. (2018). Learning by enacting: The role of embodiment in chemistry education. *Learning and Instruction*, *55*, 80–92. https://doi.org/10.1016/j.learninstruc.2017.09.008

Sweller, J. (1999). *Instructional design in technical areas.* ACER Press.

Tam, C.-O. (2015). Three cases of using object-based learning with university students: A comparison of the rationales, impact and effectiveness. In H. J. Chatterjee & L. Hannan (Eds.), *Engaging the senses: Object-based learning in higher education* (pp. 117-123). Routledge.

Tang, M., Ginns, P., & Jacobson, M. J. (2019). Tracing enhances recall and transfer of knowledge of the water cycle. *Educational Psychology Review*, *31*(2), 439–455. https://doi.org/10.1007/s10648-019-09466-4

Tulving, E. (1977). Episodic and semantic memory. In E. Tulving and W. Donaldson (Eds.), *Organization of memory* (pp. 381-403). Academic.

Taylor, M. M., Lederman, S. J., & Gibson, R. H. (1973). Tactual perception of texture. In Carterette, E. & Friedman, M. (Eds.), *Handbook of Perception Vol. III* (pp. 251-272). Academic Press.

Wilson, P. F., Stott, J., Warnett, J. M., Attridge, A., Smith, M. P., & Williams, M. A. (2017). Evaluation of touchable 3D-printed replicas in museums. *Curator: The Museum Journal*, *60*(4), 445–465. https://doi.org/10.1111/cura.12244

Wing, A., Giachritsis, C., & Roberts, R. (2007). Weighing up the value of touch. In Pye, E. (Ed.), *The power of touch: Handling objects in museum and heritage contexts* (pp.31-44). Left Coast Press.

Yeo, L. M., & Tzeng, Y. T. (2019). Cognitive effect of tracing gesture in the learning from mathematics worked examples. *International Journal of Science and Mathematics Education*, *18*, 733–751. https://doi.org/10.1007/s10763-019-09987-y

Zacharia, Z. C. (2015). Examining whether touch sensory feedback is necessary for science learning through experimentation: A literature review of two different lines of research across K-16. *Educational Research Review*, *16*, 116–137. https://doi.org/10.1016/j.edurev.2015.10.001

Appendix

Appendix A

Declaration according to § 5 Abs. 2 No. 8 of the PhD

regulations of the Faculty of Science

Collaborative Publications

EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

Mathematisch-Naturwissenschaftliche Fakultät

Erklärung nach § 5 Abs. 2 Nr. 8 der Promotionsordnung der Math.-Nat. Fakultät
-Anteil an gemeinschaftlichen Veröffentlichungen-
Nur bei kumulativer Dissertation erforderlich!

Declaration according to § 5 Abs. 2 No. 8 of the PhD regulations of the Faculty of Science
-Collaborative Publications-
For Cumulative Theses Only!

Last Name, First Name: Novak, Magdalena

List of Publications

1. Novak, M., & Schwan, S. (2020). Does touching real objects affect learning? *Educational Psychology Review*. https://doi.org/10.1007/s10648-020-09551-z

2. Novak, M., & Schwan, S. (submitted). The effects of touching real objects on learning science-related issues

3. Novak, M., Phelan, S., Lewalter, D. & Schwan, S. (2020). There is More to Touch Than Meets the Eye: Haptic Exploration in a Science Museum. *International Journal of Science Education*. http://dx.doi.org/10.1080/09500693.2020.1849855.

Nr.	**Accepted publication yes/no**	**List of authors**	Position of candidate in list of authors	Scientific ideas by the candidate (%)	Data generation by the candidate (%)	Analysis and Interpretation by the candidate (%)	Paper writing done by the candidate (%)
			Optionally, you can also declare the above-stated categories in a written statement on a separate sheet of paper.				
1	Yes	Novak, Magdalena Schwan, Stephan	1	90 %	100 %	95 %	85 %
2	No	Novak, Magdalena Schwan, Stephan	1	90 %	100 %	95 %	90 %
3	Yes	Novak, Magdalena Phelan, Siëlle Lewalter, Doris Schwan, Stephan	1	80 %	50 %	85 %	75 %

I confirm that the above-stated is correct.

____

Date, Signature of the candidate

I/We certify that the above-stated is correct.

____

Date, Signature of the doctoral committee or at least of one of the supervisors

Appendix B

Study 1

Novak, M., & Schwan, S. (2020). Does touching real objects affect learning? *Educational Psychology Review*. https://doi.org/10.1007/s10648-020-09551-z

Educational Psychology Review
https://doi.org/10.1007/s10648-020-09551-z

INTERVENTION STUDY

Does Touching Real Objects Affect Learning?

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Abstract

Based on theories of multimedia learning, the present study investigated whether the haptic sense serves as an additional channel to enhance the learning experience and learning outcomes. We therefore set up an experimental exhibition with two showrooms. In the first showroom, the sensory access of the participants to the exhibition objects was systematically varied in a 2 × 2 design with the between-subjects factors vision and haptics. While one group of participants could touch and see the objects, others could either only see or only touch them. The fourth group of participants found a showroom without objects. To address the auditory access, all participants were provided with information about each object via an audio guide. In the second showroom, further information was presented using posters. This showroom was the same for every participant. We aimed to investigate whether the haptic experience in the first showroom served as a motivator to engage further with the topic. The participants filled out questionnaires before visiting the first showroom, after visiting the first showroom, and after visiting the second showroom. To investigate the differences between the experimental groups on different outcomes, a memory test, a knowledge test, and various motivational-affective scales were used. The long-term effects of the information presentation were measured after 3 weeks. We found an advantage for recalling the objects and a heightened negative affect due to the haptic experience. Implications and further directions for this research will be discussed.

Keywords Haptics · Multimedia learning · Situational interest · Memory · Real tangible objects

The haptic sense is an indispensable part of our everyday life. It plays an important role when we try to find the light switch at night, when we want to assess the ripeness of an avocado, or for social interaction with our fellow human beings, such as hugging and shaking hands. Therefore, the haptic sense is crucial for interacting with the environment and with each other, forming an integral part of our multimodal system (Minogue and Jones 2006; Smith and

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Gasser 2005). Although touch plays an important role in exploring and getting to know the world around us, it has been far less researched than visual and auditory senses (Gallace and Spence 2009), and it is often neglected in learning theories, especially in multimedia learning theories. To help to fill this research gap, the present study uses a multi-criteria approach to investigate the influence of haptic exploration of real, three-dimensional, tangible objects on learning experience and learning outcomes. We are interested in the question of whether the haptic sense—together with the visual and auditory senses—can serve as an additional channel for comprehending the learning material and thus support the learning process.

Bodily Experiences as Resources for Learning

In recent years, the importance of bodily experiences for mental processes has been established both theoretically and empirically, demonstrating that cognition is closely intertwined with the sensorimotor characteristics of human bodies (Barsalou 2010; Glenberg et al. 2013; Wilson 2002). In this view, cognition is instantly coupled with the present environment through bodily activities. If possible, external resources are exploited in order to situate cognitive processes, thereby simplifying mental routines, minimizing errors, and decreasing cognitive load (embedded cognition; Pouw et al. 2014). Also, information from the environment is not simply passively registered. Instead, the human body constitutes a fine-tuned perceptual system, which explores its surrounding by an intricate interplay of motor behavior (including movements of the eyes, the head, the limbs, or the whole body) and sensory receptors (including eyes, ears, nose, tongue, and skin; Gibson 1966). While seeing, hearing, and smelling gather information from a distance, touching (and tasting) brings the body in direct contact with other beings, artifacts, or materials. With few exceptions, like dark or noisy conditions, both vision, hearing, and touch work in concert (Hollins 2010). Accordingly, the development of eye movements in service of goal-directed vision during early childhood is paralleled by a corresponding development of motor behavior (touching, grasping) in service of manual scrutinization of objects, eventually resulting in a set of haptic exploratory routines (Lederman and Klatzky 1987, 2009).

Embodied cognition does not only support successful behavior in a given situation but extends to “offline” cognition as well. According to the perceptual symbol system account, sensorimotor input will be permanently stored in long-term memory and can be re-instantiated even when the mental apparatus is decoupled from the original situation in which the embodied experience took place (Barsalou 2010; Wilson 2002). Thus, sensorimotor experiences constitute fundamental elements of mental representations, which allow for successfully coping with future situations (Glenberg 1997).

Within this framework of embodiment, haptic exploration may contribute to offline cognition and learning in several ways. Firstly, it adds an additional layer of sensorimotor input, contributing to an enriched mental representation that can be easily accessed and re-instantiated (Hutmacher and Kuhbandner 2018; Lacey and Sathian 2014). Secondly, re-activation of stored efferent activities may be fed into forward models which allow the cognitive system to emulate actions in an offline manner (Glenberg et al. 2013; Grush 2004). In this way, haptic-based motor imagery complements visual imagery, resulting in mental simulations of possible uses of objects, tools, or materials, as evidenced by increased frequencies of gestures during verbal descriptions of object manipulations (Hostetter and Alibali 2008; Kamermans et al. 2019).

Thirdly, according to Paas and Sweller (2012), object manipulation is a privileged type of learning that allows for acquiring biologically primary knowledge; that is, humans are evolutionarily disposed to acquire knowledge through manual exploration of objects in an unconscious, effortless, rapid, and intrinsically motivated manner, for which the constraints of working memory with limited capacity do not apply. Accordingly, due to its highly motivating character and its ease of acquiring knowledge and skills, this "natural" mode of learning plays a great role outside of formal learning contexts from early childhood on (Geary 2008). But, it may also be successfully utilized to support acquiring biologically secondary knowledge in educational settings (Paas and Sweller 2012; Pouw et al. 2014), with examples ranging from finger tracing to hands-on experimentation to re-enactments (e.g., Stull et al. 2018; Tang et al. 2019; Zacharia 2015).

Facets of Haptic Exploration

While passive touch means being touched by a stimulus or a person, for example, by an object being pressed against the skin, active touch implies that someone chooses to explore and manipulate an object manually to obtain information about the properties of the object (Minogue and Jones 2006). Such haptic exploration includes several different sensations that may contribute to the learning experience. Firstly, it is typically based on hand movements. Similar to gestures, such coordinated muscular movements can be considered examples of embodied cognition, resulting in memory traces that make an additional contribution to the mental representation of the phenomenon or concept explored (Pouw et al. 2014). Accordingly, research on finger tracing has demonstrated that learners benefit from tracing a certain shape (for example, temperature curves or the water cycle) with the index finger (Agostinho et al. 2015; Ginns et al. 2016; Tang et al. 2019). According to Fiorella and Mayer (2016), tracing can be considered to be one example of learning by enacting, meaning that task-relevant movements are integrated into the learning process, thereby fostering generative learning.

Secondly, haptic exploration may transmit information about an object's material qualities, including texture, weight, consistency, and temperature (Minogue and Jones 2006). Lederman and Klatzky (1987) identified different exploratory procedures to classify stereotypical hand movements that adults use to explore objects with the haptic sense to obtain information on its properties. For example, the pressure was used to acquire information on the object's hardness (Lederman and Klatzky 1987, 2009). These forms of exploration lead to a maximization of the sensory input and facilitate the encoding process. Accordingly, Montessori pedagogy has extended finger tracing by using sandpaper letters that provide additional tactile stimulation via the letters' texture (Montessori 1912). This teaching technique involves input from several modalities at the same time to explore a letter: Students feel the way the letter is written while they touch and trace its contours, and at the same time, they look at its representation and listen to the sound of the letter pronounced by their teacher. Bara et al. (2004) found that using the haptic channel additionally increased the positive effects of the training on the decoding skills of children as well as their understanding and use of the alphabetic principle.

Thirdly, haptic exploration may provide detailed information about an object's shape and the three-dimensional configuration of its parts. Particularly in science and medicine education, haptic interaction with three-dimensional models is used to foster comprehension of relevant spatial layouts, such as molecular configurations or anatomical structures. In a recent study, Stull et al. (2018) examined the impact of enactment with 3D molecular models on chemistry learning in video and classroom lectures. The students in both learning contexts learned more if they enacted the demonstration than if they just watched the demonstration. They also found that learning by enacting was stable over a period of several days between instruction and testing. Similarly, Smith (2016) used 3D-printed biological molecules as active learning tools to enhance learning in a lecture hall. The students reported the value of the models for understanding the learning contents and showed a high level of engagement during the learning session.

Acquiring Knowledge About Tools and Artifacts via Object-Based Learning

Taken together, haptic exploration should be considered a compound experience including motor stimulation, perception of material qualities, and information about shape and spatial configuration. While to date most of the empirical research on this topic has focused on abstract learning material, like molecular models, letters, or diagrams, similar effects have also been postulated for real objects. The pedagogical concept of object-based learning (OBL) posits that haptic interaction with real tangible objects can serve important roles in the learning process and encourages students to link these experiences to abstract ideas and concepts (Chatterjee et al. 2015; Rowe 2002). OBL is based on a multisensory, constructivist approach. By integrating haptics with other senses, such as vision and audition, it is assumed that learners develop their knowledge and understanding through interaction with objects. OBL is based on Kolb's experiential learning cycle (Kolb 1984), which—referring to Dewey (1899) and Piaget (1929)—links the four areas of (1) "concrete experience/feeling": a new experience is gained or an existing experience is reinterpreted; (2) "reflective observation of the experience"; (3) "abstract conceptualization/thinking": the reflection helps to raise a new idea or to modify an existing concept; (4) "active experimentation/doing": the new idea is applied, and the learner observes what happens. The learning cycle may be entered at each point, but the stages should be followed in sequence. As the name of the theory implies, the learner must be actively involved in the experience to acquire real knowledge. But also, the reflection on the experience and the use of analytical skills to conceptualize the experience is important to apply new knowledge. A qualitative study with semi-structured interviews showed that the combination of vision and the haptic sense led to higher levels of engagement and enhanced knowledge and understanding (Sharp et al. 2015). Tam (2015) conducted three case studies on OBL and showed that the haptic exploration of the objects led to a more intense learning experience. Students reported that touching sculptures feels more reliable than just seeing them, that it can enhance the understanding of the objects, and help to correct misconceptions.

OBL's emphasis on concrete haptic experiences with real objects seems to be particularly well suited for domains of knowledge in which human artifacts and tools play a prominent role, as is the case in many vocational fields. More specifically, haptic exploration may help users to detect affordances, that is, functional properties of artifacts in service of goal-directed actions (Gibson 1966, 1979). For example, simple mechanical interactions with hand-held tools allow users to judge their suitability for a diverse range of activities, like hammering, scraping, poking, or hooking (Harrison et al. 2011; Michaels et al. 2007).

While in Gibson's initial conception affordances are directly perceived without the necessity of internal representation, recent models assert that the knowledge of affordances can be stored in long-term memory and activated in subsequent contexts (Osiurak and Badets 2016). For example, Gredlein and Bjorklund (2005) found that children who engaged in manual play with a range of objects during free play were more successful in choosing appropriate tools for solving a task in a later situation. Furthermore, manipulation knowledge which is acquired by haptics and vision is linked to functional and mechanical knowledge (Remigereau et al. 2016). Whereas functional knowledge concerns information about the context in which a tool can be used together with the objects usually used with that tool, mechanical knowledge addresses the underlying physical and technical principles, allowing one to form a mental simulation of the tool use in action (Osiurak and Badets 2016; Remigereau et al. 2016). Taken together, according to current models of tool use, haptic exploration allows for generating manipulation knowledge, which, in concert with functional and mechanical knowledge, forms an embodied representation of one's knowledge about a given artifact or tool.

Most research in the field of tool use has dealt with simple, everyday tools (like hammers or knives) and can therefore be interpreted as a typical case of evolutionary evolved biologically primary knowledge (Geary 2008; Vaesen 2012), with learning taking place more or less playfully in an unconscious, effortless, rapid, and intrinsically motivated way. But in the light of instructional uses of embodied cognition (Geary 2008; Paas and Sweller 2012), making use of the mechanisms of biologically primary knowledge acquisition through the haptic exploration of material objects may also foster the learning of biologically secondary knowledge, particularly for contents that include information about unfamiliar tools or human artifacts.

Cognitive-Affective Theory of Learning with Media (CATLM) as a Framework for the Role of Haptics in Learning

The haptic exploration of objects in service of secondary learning normally takes place in concert with other types of learning materials, like verbal explanations, texts, or illustrations. Accordingly, the provision of touchable objects can be considered an extension of multimedia learning. Multimedia learning environments present information via various sensory channels, such as vision and audition, or via various sign systems, such as texts and illustrations (Mayer 2014). Several theories have been proposed that explain the cognitive learning effects of multimedia, mainly focusing on combinations of textual and pictorial material (Mayer 2014; Paas and Sweller 2014; Schnotz 2014).

The cognitive-affective theory of learning with media (CATLM, Moreno and Mayer 2007) extends these approaches in two ways. Firstly, it adopts the three basic assumptions of the cognitive theory of multimedia learning (Mayer 2014), namely: (1) information processing using two or more channels (Baddeley 1992; Paivio 1986), (2) the limited capacity of working memory (Sweller, 1999), and (3) active knowledge construction and active information processing as a prerequisite for successful learning (Mayer and Moreno 2003), but it supplements them with four additional assumptions, including (a) that long-term memory consists of a semantic and an episodic memory and has a dynamic structure (Tulving 1977), (b) that learning is mediated by motivational and affective factors by increasing or decreasing cognitive interrelations with the content (Pintrich 2003), (c) that metacognitive factors are supposed to influence learning with multimedia by regulating cognitive and affective processes (McGuinness 1990), and (d) that differences in prior knowledge and abilities of learners influence learning success (Kalyuga et al., 2003). Hence, CATLM explicitly takes the influence of motivational and affective factors and metacognition on learning with multimedia into account (Moreno and Mayer 2007).

Secondly, although CATLM emphasizes the importance of the auditive and the visual channel for accessing learning material, it also considers tactile, olfactory, and gustatory sensory input as additional information sources that may affect the learning process (Chan and Black 2006; Moreno and Mayer 2007). In addition, an emphasis is placed on the learners' interaction with the multimedia content, including manipulation of the presented material. Therefore, CATLM affirms the relevance of physical materials as a means for learning. This may include, for example, physical models in chemistry and medicine (Smith 2016; Stull et al. 2018), hands-on elements in Montessori pedagogy (Bara et al. 2004), or in science exhibitions (Afonso and Gilbert 2007; Skydsgaard et al. 2016) together with the recent development of digital force-feedback devices and 3D printing (Di Franco et al. 2015; Wilson et al. 2017) but also material objects like artifacts and tools (Chatterjee et al. 2015).

Both by introducing haptics into multimedia learning and by supplementing the core cognitive effects of multimedia material with possible effects on motivation, affect, and metacognition, CATLM provides a general framework for conceptualizing the role of haptics for learning experiences and learning outcomes. Therefore, we will discuss relevant empirical findings on the role of haptics for learning organized along with the components of the CATLM model: situational interest, attention and information selection, processing in working memory, storage in long-term memory, and affect.

Cognitive and Motivational Effects of Haptic Exploration

Situational Interest, Attention, and Information Selection

Studies on the effects of the provision of haptic exploration on situational interest and information selection have been primarily conducted in museum settings. In line with the assumption that acquiring biologically primary knowledge, for example, tool use, is intrinsically motivating, it was found that objects had both a higher attention catch and attention hold if they can be haptically explored (Di Franco et al. 2015; Koran et al. 1984; Wilson et al. 2017). Koran et al. (1984) showed an increase in the number of visitors entering the gallery when the exhibits could be haptically explored. Studies by Di Franco et al. (2015) and Wilson et al. (2017) found that museum visitors favored 3D prints and replica over original artifacts because the former allow for a haptic experience of the objects.

Research also indicates that haptics may be utilized to support the acquisition of secondary knowledge. For example, students of a biochemistry course identified touchable physical models as the most preferred and useful learning tools compared with other types of learning materials (Harris et al. 2009; Roberts et al. 2005). Also, Roberts et al. (2005) found that the availability of touchable models in a biochemistry course captured the students' interest in molecular structure and function, resulting in the formulation of more sophisticated questions on this topic. Therefore, in line with the assumptions of object-based learning, the haptic exploration of objects may constitute an initial step for approaching a certain topic, motivating learners to deal further with the subject (Chatterjee et al. 2015). Based on these findings, one can assume that objects which can be touched seem to attract attention and are preferred over objects which can be only looked at, that the increased interest in a topic can lead the learners to deal more intensively with the topic, and that they are motivated to engage in further information seeking on this topic.

Processing in Working Memory and Storage in Long-Term Memory

Recent studies demonstrate that haptic experiences of objects lead to detailed and durable long-term memory representations, indicating that touch constitutes an important sensory channel of environmental information on its own (Hutmacher and Kuhbandner 2018). Additionally, processing in working memory integrates haptic experiences with information from other sensory channels. According to Johnson et al. (1989), haptic inputs activate tactile representations, which in turn activate visual representations, in the case of familiar objects also triggering the object's name. Thus, in cases of fully compatible inputs from vision and haptics, as when an object is looked at while touching it, a unified, multimodal representation is built (Hollins 2010). Accordingly, cross-modal recognition tests show high degrees of accuracy in recognizing objects visually after participants were blindfolded and had explored the objects with their hands (Hutmacher and Kuhbandner 2018; Lacey and Sathian 2014).

Due to its nature as a source of biologically primary knowledge, the use of the haptic sense may reduce the cognitive load required for the acquisition of biologically secondary knowledge (Paas and Sweller 2012). Similarly, according to the embedded cognition claim, perceptual and interactive richness of haptic experiences may alleviate the cognitive load by embedding the learner's cognitive activity in the environment (Pouw et al. 2014). Also, some authors have argued further that the permanent availability of haptic information during learning can be seen as an instance of cognitive offloading, thereby reducing extraneous cognitive load and freeing working memory resources for enhanced elaboration (Manches and Malley 2012; Pouw et al. 2014). Empirical research on finger tracing showed mixed results concerning the positive effect of tracing on cognitive load. While some studies failed to show a reduction in perceived cognitive load through tracing (Agostinho et al. 2015; Ginns et al. 2016; Korbach et al. 2020; Macken and Ginns 2014), other studies found that tracing can have a positive effect on test item difficulty ratings, which can be interpreted as a measurement of intrinsic cognitive load (Du and Zhang 2019; Hu et al. 2015; Yeo and Tzeng 2019). In a recent study, it was found that primary school students who traced while studying learning material about the water cycle showed lower extraneous—but not intrinsic—cognitive load than students who were not allowed to trace (Tang et al. 2019).

Finally, while it has been argued that the perceptual richness of objects may hinder the learners' ability to identify intended underlying principles or symbolic meanings (Kaminski et al. 2009; Uttal et al. 2009), this view has been criticized from the perspective of embodied cognition accounts (Pouw et al. 2014). In particular, it has been argued that learning from manipulatives often includes internalization of sensorimotor routines without a change from concrete to abstract representation, as long as the information provided by manual exploration stands in close relationship to the abstract contents to be learned. For example, a recent study by Bara and Kaminski (2019) found that children who held objects in their hands while learning the corresponding foreign language vocabulary memorized the words better than those who saw the respective pictures of the objects during learning. This close relationship between sensorimotor and semantic information is particularly evident for the acquisition of knowledge about tools and artifacts. As has been discussed above, during learning, the manipulation knowledge that is acquired by haptics and vision is linked to functional knowledge about the contexts and conditions of using the respective artifact (Remigereau et al. 2016). Hence, taken together, the findings indicate that haptic exploration contributes to a rich multimodal representation which may also be linked to abstract concepts, thereby facilitating retention and transfer.

Affect

Although CATLM also considers the affective effects of multimedia learning materials, to the best of our knowledge, systematic research on affective effects of haptic exploration in educational contexts is virtually absent. Yet, findings in the field of consumer research have shown that affective responses can be evoked by the sensory feedback elicited by the act of touching (Peck and Shu 2009; Peck and Wiggins 2006). Peck and Childers (2003) pointed out that especially individuals with a high need for touch consider touch to be a way to experience pleasure and enjoyment and engage in touch because it is fun, interesting, and enjoyable. Etzi et al. (2016) found that different tactile textures are associated with words expressing different emotional states. Some studies have shown that touching certain objects (e.g., honey or worms) can induce the feeling of unpleasantness and disgust (Oum et al. 2011; Skolnick 2013). The results of these studies thus indicate that, depending on the type of object, haptic exploration can evoke and intensify either positive or negative affective reactions.

The Present Study

The previous discussion indicates that, in line with the assumptions of CATLM, the haptic exploration of real objects, like tools and artifacts, can have a positive impact on situational interest and the selection of information, and on the processing in working memory, including integration with other sensory modalities as well as more abstract information. This positive impact also extends to storage in long-term memory and to motivation to deal further with the subject matter exemplified by the objects. Therefore, the present study used a multi-criteria approach to investigate the influence of haptic exploration of real objects on learning experience and learning outcomes. A museum context was chosen because it is characterized by the self-determination and the intrinsic motivation of learners and is thus particularly useful for the investigation of motivational and cognitive learning effects (Lewalter and Geyer 2009; Schwan et al. 2014). As part of a larger project on the presentation of conflicting issues in exhibitions, we set up an experimental exhibition on the topic “animal husbandry, breeding, and welfare” which consisted of two showrooms. In the first showroom, the sensory access of the participants to the exhibition objects, consisting of six tools typical of animal husbandry and breeding, was systematically varied in a 2 × 2 design with the between-subjects factors vision (yes: objects visible/no: objects not visible) and haptics (yes: objects touchable/no: objects not touchable). To provide a rich multimodal learning experience, all of the participants were provided with additional information about each tool via an audio guide. In a second showroom, further information on themes related to the tools was presented using posters with texts, illustrations, and diagrams. The second showroom was the same for every participant. We aimed to investigate whether the haptic experience in the first showroom served as a motivator to engage further with the topic.

Referring to CATLM (Moreno and Mayer 2007), we hypothesized that the more sensory channels are used during knowledge acquisition, the more intense the engagement with the learning content should be. Thus, touching objects while looking at the object was expected to be better than touching them without vision or looking at them without touching, which in turn should be better than neither seeing nor touching the objects. In particular, we assumed (1) a heightened attention catch and attention hold of the objects, which should be shown by an increased duration of stay (length of time spent in each showroom), an increased number of objects inspected, and an increased situational interest in the first showroom, and (2) we assumed an increase in memory for the objects and a better performance in a knowledge acquisition test that should appear (a) directly after the exhibition and (b) in a follow-up. We also hypothesized a transfer of the beneficial effects of haptic exploration in the second showroom, which should manifest in (3) an increased duration of stay, an increased number of posters read, and a greater situational interest in the second showroom together with (4) a better comprehension of the contents of its textual material. In addition, we investigated the affective differences between the experimental groups during the exploration of the two showrooms. We assumed that the participants who could touch objects in the first showroom will report more intensive affective states than the participants who were not allowed to touch the objects (5).

Method

Participants

Participants were recruited from our institute's mailing list. They were required to be native German speakers. Assuming medium effect sizes and a power of .80, a power analysis using GPower recommended sample size of $n = 158$ participants. We decided to recruit 160 participants (40 per condition). Excluded participants were replaced by other participants. From the 174 recruited participants, eleven had to be excluded because they had not followed the instructions properly or because of technical difficulties. The remaining 163 participants ranged in age between 18 and 66 years ($M = 24.76$, SD = 7.55); 120 of them (73.6%) were female, 42 (25.8%) were male, and one (0.06%) was diverse (non-binary). Most of the participants (93.3%) were students from a broad variety of disciplines. The research was approved by the institutional review board of our institute. All of the participants provided written informed consent before participating in this study and were paid for their participation.

Design

We used a 2 × 2 between-subjects design with the factors vision (yes/no) and haptics (yes/no). The participants were randomly assigned to one of the four experimental conditions: no-object condition ($n = 42$), only-vision condition ($n = 40$), only-haptics condition ($n = 42$), and vision-and-haptics condition ($n = 39$). Three weeks after visiting the experimental exhibition, the participants were requested to fill out an online survey as a follow-up. A total of 115 participants took part in this follow-up (no-object condition, $n = 29$; only-vision condition, $n = 27$; only-haptics condition, $n = 29$; vision-and-haptics condition, $n = 30$).

Materials

Showroom 1 In the first showroom, methods used in conventional dairy cow and pig farming were both demonstrated with the help of three tools that are typically used in animal husbandry and breeding, namely, a milking machine, an insemination gun with a veterinary glove, and a dehorning device for cow farming, and castration forceps, a massage brush, and a heat cutter for pig farming (see Fig. 1). The tools were complex tools that are not commonplace and unknown to most people. In the only-vision condition and the vision-and-haptics condition, the objects were put on museum pedestals. In the only-haptics condition, the objects on the pedestals were put into feeler boxes to ensure that the objects could be touched but not seen by the participants. In the no-objects condition, the museum pedestals remained empty. To remind the participants of the corresponding instruction, we had signs—similar to those in a museum—hung up: “Please do not touch,” “Please touch,” and “Feel it.” In order to address the auditory channel, all of the participants were provided with information about each exhibit via an audio guide. The auditory device was completely controllable by participants. They could start, stop, fast forward, and rewind the audio texts. The six audio texts lasted about 2 min each.

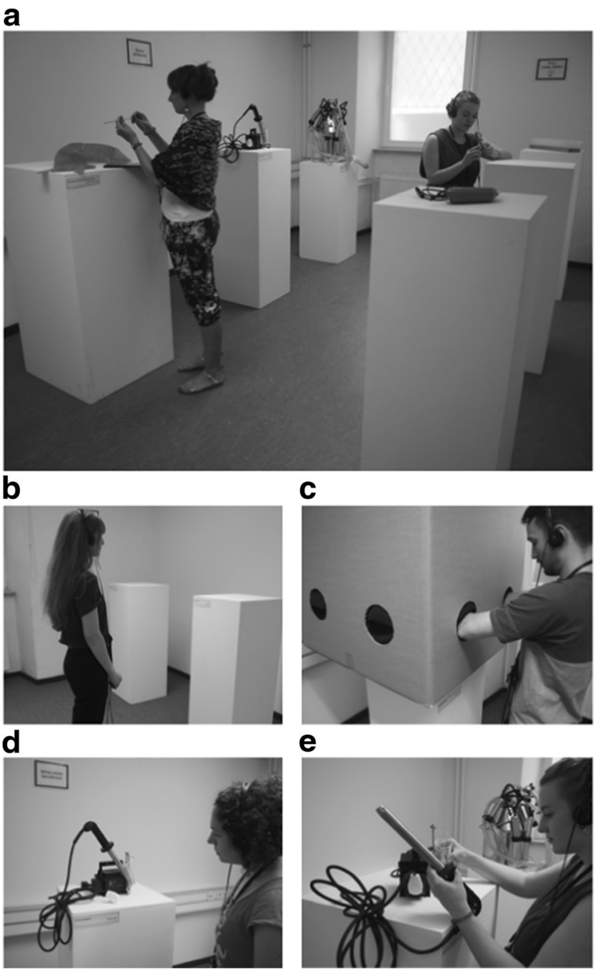

Fig. 1 In the first showroom, tools that are typically used in animal husbandry and breeding were presented. **a** Overview of the first showroom in the vision-and-haptics condition; **b** participant in the no-objects condition; **c** participant in the only-haptics condition; **d** participant in the only-vision condition; **e** participant in the vision-and-haptics condition

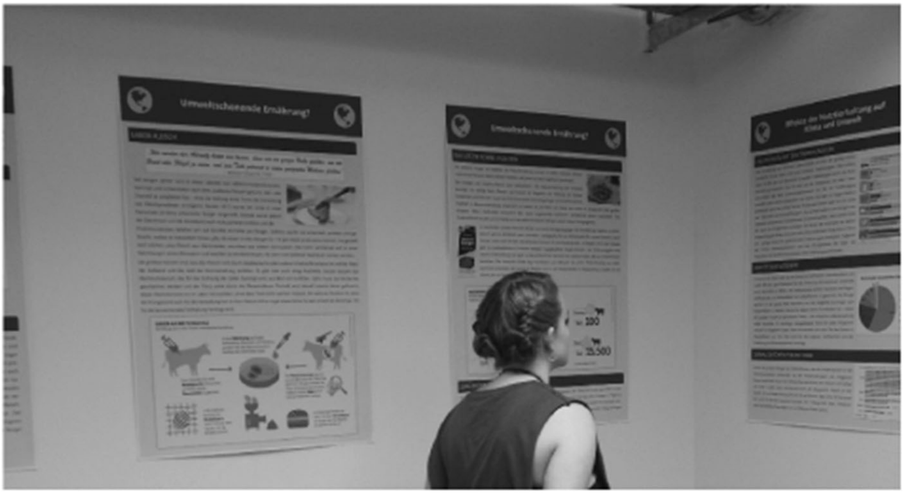

Fig. 2 In the second showroom, posters with further information on animal husbandry and breeding were presented

Showroom 2 For each object, further information on a related topic was provided by posters in the second showroom (see Fig. 2; e.g., showroom 1: a milking machine and an audio text about the history and use of milking machines were presented; showroom 2: the life of a dairy cow was explained). We also presented four posters with more general topics (nutrition, climate, and environment). In total, we presented twelve posters which were vividly designed using a combination of texts, illustrations, and diagrams.

Measures

The participants were asked to fill out questionnaires on an iPad mini before visiting the first showroom, after visiting the first showroom, and after visiting the second showroom. The follow-up was conducted via a Qualtrics online survey and could be filled out at home. The following scales and tests were used:

Self-reported Prior Knowledge

Seven items answered on a 5-point Likert-type scale (1 "not at all" to 5 "very well"; e.g., "How well are you acquainted with the following topics? – livestock husbandry") asked the participants how good they self-evaluate their knowledge on different aspects of the exhibition's topic. An average prior knowledge score was calculated from the sum of all responses divided by the total number of items (Cronbach's $\alpha = .874$).

Prior Interest

Prior thematic interest in the topic of the exhibition was measured by four items on a 5-point Likert-type scale (1 "not at all" to 5 "very"; e.g., "I am interested in the topic of livestock husbandry."). An average interest score was calculated by the sum of all responses divided by the total number of items (Cronbach's $\alpha = .844$).

Attention and Information Selection

In the museum context, attention and information selection is often operationalized by attention catch (What is observed?) and by attention hold (How long is it observed?) (Serrell 1997). In addition to direct observation or measuring the duration of stay, questionnaires can be used to measure attention catch and attention hold (Lewalter and Geyer 2009). Accordingly, three indicators were collected in our study: the duration of stay, the number of objects inspected in the first showroom (posters in the second showroom), and a German scale on situational interest (Lewalter and Geyer 2009). In the model of Hidi and Renninger (2006), situational interest constitutes a first step in the development of interest by becoming spontaneously attracted to certain content. According to Lewalter and Geyer (2009), two phases of situational interest can be distinguished: (1) SI-catch in which attention of a person is drawn and curiosity is aroused, and (2) SI-hold which describes the intention to maintain attention to the contents and spend more time on them (Hidi and Renninger 2006; Lewalter and Geyer 2009). We collected these variables for the first and the second showroom. Whereas the results of the first showroom served as indicators for differences in attention and information selection processes, the results of the second showroom indicated whether the participants differ in their motivation to engage themselves with further information on the exhibition topic due to their experience in the first showroom.

Number of Objects Inspected and Posters Read After each showroom, we asked the participants to indicate on a plan of the showroom which of the exhibition contents they had inspected. In both conditions in which touching was allowed, we asked them to indicate whether they had touched the tools in the first showroom. If they had touched fewer than four objects, they were excluded from the analysis. In the only-vision condition, the participants were asked to indicate whether they had touched the tools. If they had touched more than two objects, they were excluded from the analysis.

Duration of Stay The observation time in both showrooms was measured by the iPad mini.

Situational Interest (Attention Catch and Attention Hold) We used an adapted German scale for situational interest (Knogler et al. 2015; Lewalter and Geyer 2009; Lewalter 2020) which distinguishes between the two phases of situational interest: (1) SI-catch, and (2) SI-hold. Accordingly, the scale included two subscales with six 5-point Likert-type scale (1 "not at all" to 5 "very much") items each for attention catch (e.g., "The exhibition captivated my attention.") and attention hold (e.g., "I would like to know more about parts of the exhibition."). Due to the strong correlation between both subscales ($r = .596$, $p = 0.01$), we analyzed them as one scale. We measured situational interest after the first showroom (Cronbach's $\alpha = .893$) and after the second showroom (Cronbach's $\alpha = .910$).

Recall of Objects

We asked the participants to list all of the objects of the first showroom. An answer was considered correct if the participants listed the correct name or if it was clear from the description that the function of the tools was understood. A total of six points could be achieved. The evaluator of the recalled objects was blinded to the experimental condition. Ten percent of the answers were randomly chosen and rated by two independent raters. The inter-rater agreement was 97.45%.

Knowledge Acquisition Test

In the knowledge acquisition test, 32 self-developed multiple-choice questions with four response options (one correct) were asked (e.g., "Approximately how old is a dairy cow when she is inseminated for the first time?" – (a) 12 months, (b) 16 months, (c) 24 months, (d) 28 months; "What is the procedure for dehorning?" (a) The roots of the horns are pinched off with pliers, (b) The roots of the horns are sawn off, (c) The horn buds are cut away, (d) The horn buds are removed by heat; "Which tool is used to cut the curly tails?" (a) pliers, (b) heat cutter, (c) scalpel, (d) scissors.) Twelve questions addressed the first showroom, and 20 questions addressed the second showroom. We used the knowledge acquisition test in the second posttest (directly after visiting the exhibition) and in the follow-up (3 weeks after visiting the exhibition). While the internal consistency of the knowledge acquisition test concerning the first showroom was low (Cronbach's $\alpha_{\text{after exhibition}} = .342$ and Cronbach's $\alpha_{\text{follow-up}} = .331$), the internal consistency of the knowledge acquisition test concerning the second showroom was acceptable (Cronbach's $\alpha_{\text{after exhibition}} = .703$ and Cronbach's $\alpha_{\text{follow-up}} = .652$).

Need for Touch

To access the individual preference for haptic information, we used a German version (Nuszbaum et al. 2010) of the need for touch (NFT) scale by Peck and Childers (2003). It consisted of 14 items answered on a 5-point Likert-type scale (1 "not at all" to 5 "very much"; e.g., "When walking through stores, I can't help touching all kinds of products."). An average score for the need for touch was calculated by the sum of all responses divided by the total number of items (Cronbach's $\alpha = .950$).

The Composite Respect for Animals Scale

To measure attitude towards animals and the use of them, we used six components of the short version of the German Composite Respect for Animals Scale (CRAS-S; Randler et al. 2018). Each component was measured by two items on a 5-point Likert-type scale (1 "fully agree" to 5 "fully disagree," e.g., "I think it is perfectly acceptable for animals to be raised for human consumption."). Since one item was excluded due to a bad item characteristic ($r = .162$), the construct was measured by 11 items, and an average score was calculated by the sum of all responses divided by the total number of items (Cronbach's $\alpha = .793$).

Positive Affect and Negative Affect Schedule

The participants' affective states were measured with the German version of the Positive Affect and Negative Affect Schedule (PANAS; Breyer and Bluemke 2016; Watson et al. 1988) which consists of ten items for positive (e.g., "enthusiastic," "inspired") and ten items for negative affect (e.g., "upset," "ashamed"). Both positive and negative affect were measured on a 5-point Likert-type scale (1 "not at all" to 5 "extremely"). We used the PANAS before the exhibition, after the first and after the second showroom. Two average scores (for positive and negative affect) were calculated by the sum of all responses divided by the total number of items (positive affect: Cronbach's $\alpha_{\text{before exhibition}} = .853$, Cronbach's $\alpha_{\text{after showroom 1}} = .792$, Cronbach's $\alpha_{\text{after showroom 2}} = .829$; negative affect: Cronbach's $\alpha_{\text{before exhibition}} = .819$, Cronbach's $\alpha_{\text{after showroom 1}} = .886$, Cronbach's $\alpha_{\text{after showroom 2}} = .882$).

Procedure

After reading the information about the study and signing the informed consent, the participants were asked to fill out the PANAS, the prior knowledge test, and the prior interest scale. Then, they were invited to visit the first showroom and explore it freely at their own pace and interest. The participants were instructed to leave their personal belongings, like coats, bags, and smartphones in the room where the surveys took place. Depending on the experimental condition, they were instructed to either touch and explore or not to touch the objects. The participants in the no-objects condition were informed that it had not been possible to procure the objects. All of the participants were instructed to use the iPad as an audio guide for each exhibit in the first showroom. Following the visit, the participants were then asked to fill out the PANAS and the situational interest scale and to indicate which tools they had inspected.

Next, the participants were led to the second showroom and were asked to explore this room at their own pace and interest. After that, the participants were asked to fill out the PANAS and the situational interest scale and to indicate which posters they had read. After playing cards for about 10 min as a filler task, the participants were asked to freely recall all of the objects that were presented in the first showroom, to fill out a knowledge acquisition test, the NFT, the CRAS-S, and questions on their sociodemographic data. The study lasted 1 to 1.5 h for each participant. The participants began the study every quarter of an hour so that they were either alone, in pairs, or in threes in one of the two exhibition rooms.

After 3 weeks, the participants were invited by e-mail to fill out the follow-up online survey, which included a self-evaluation of their knowledge and thematic interest, recalling the objects that were presented in the first showroom, and again completing the knowledge acquisition test. The completion of the online survey took about 10 min.

Results

A Priori Differences Between Groups

The participants reported a medium level of prior knowledge ($M = 2.62$, SD = 0.67) and interest ($M = 3.15$, SD = 0.85), a rather pro-animal attitude towards the use of animals ($M = 3.45$, SD = 0.60) and a medium score for the need for touch ($M = 2.48$, SD = 0.90; see Table 1). A series of two-way ANOVAs with vision and haptics as between-subjects factors showed no statistically significant differences in attitude towards the use of animals and need for touch, all $F < 2.6$, all $p > .05$.

The two-way ANOVA with self-evaluated prior knowledge as a dependent variable revealed no significant main effects of vision, $F(1,159) = 0.003$, $p = .956$, $\eta_p^2 < 0.01$, and haptics, $F(1,159) = 2.25$, $p = .136$, $\eta_p^2 = 0.01$, but a significant interaction between those two factors, $F(1,159) = 6.16$, $p = .014$, $\eta_p^2 = 0.04$. Subsequent post hoc tests (Tukey's HSD) revealed that

Table 1 Means and standard deviations for control variables

	No-objects condition M (SD)	Only-vision condition M (SD)	Only-haptics condition M (SD)	Vision-and-haptics condition M (SD)
CRAS-S*	3.53 (0.68)	3.44 (0.55)	3.35 (0.57)	3.47 (0.59)
Need for touch	2.38 (0.89)	2.36 (0.84)	2.74 (1.02)	2.44 (0.82)
Prior knowledge	2.83 (0.65)	2.56 (0.67)	2.42 (0.63)	2.67 (0.70)
Prior interest	3.32 (0.91)	3.02 (0.86)	2.95 (0.83)	3.33 (0.73)

*CRAS-S: the Composite Respect for Animals Scale

the participants in the no-objects condition rated their prior knowledge higher than the participants in the only-haptics condition.

The two-way ANOVA with self-evaluated prior interest as a dependent variable revealed no significant main effects of vision, $F(1,159) = 0.08$, $p = .779$, $\eta_p^2 < 0.01$, and haptics, $F(1,159) = 0.11$, $p = .738$, $\eta_p^2 = 0.01$, but a significant interaction between those two factors, $F(1,159) = 6.76$, $p = .010$, $\eta_p^2 = 0.04$. Subsequent post hoc tests (Tukey's HSD) showed no significant differences in the experimental groups.

Due to the significant results regarding prior knowledge and interest, we included these variables as covariates in the following analysis. Due to multiple comparisons, we conducted a Bonferroni correction for the following analysis. The adjusted α value is 0.004. To determine if any of the comparisons are statistically significant, the p value must be $p < 0.004$.

Situational Interest, Attention, and Information Selection

Duration of Stay in the First Showroom The average duration of stay in the first showroom was just under a quarter of an hour ($M = 14.40$, SD = 1.91). To test whether the groups differed in the time that they spent in the first showroom, we conducted a two-way ANCOVA with the between-subjects factors vision and haptics on the duration of stay, controlling for prior knowledge and prior interest. There were no significant differences in the duration of stay between the experimental groups in the first showroom, all $F < 3.3$.

Number of Objects Inspected Most of the participants dealt with all of the objects and the corresponding audio texts in the first showroom ($M = 5.72$, SD = 1.11). According to a two-way ANCOVA with the between-subjects factors vision and haptics, controlling for prior knowledge and prior interest, there were neither significant differences between the experimental groups nor significant effects of the covariates, all $F < 1.1$.

Situational Interest (Attention Catch and Attention Hold) The participants showed a medium to a high level of attention catch and hold, as measured by the situational interest questionnaire after visiting the first showroom ($M = 3.66$, SD = 0.65). After controlling for prior knowledge, $F(1,157) = 0.92$, $p = .340$, $\eta_p^2 = 0.01$, and prior interest, $F(1,157) = 53.56$, $p < .001$ $\eta_p^2 = 0.25$, we found no significant main effect for vision, $F(1,157) = 0.27$, $p = .606$, $\eta_p^2 < 0.01$, and no significant main effect for haptics, $F(1,157) = 4.19$, $p = .042$, $\eta_p^2 = 0.03$. There was no significant interaction effect, $F(1,157) = 0.28$, $p = .598$, $\eta_p^2 < 0.01$. Means and standard deviations of all attentional variables are shown in Table 2.

Table 2 Means and standard deviations for the duration of stay, number of objects inspected, and situational interest in the first showroom

	No-objects condition *M* (*SD*)	Only-vision condition *M* (*SD*)	Only-haptics condition *M* (*SD*)	Vision-and-haptics condition *M* (*SD*)
Duration of stay	14.04 (1.36)	14.27 (2.12)	14.62 (1.95)	14.68 (2.11)
Number of objects inspected	5.88 (0.77)	5.72 (1.04)	5.52 (1.49)	5.77 (1.01)
Situational interest	3.63 (0.58)	3.51 (0.78)	3.65 (0.60)	3.87 (0.61)

Information Processing

Recall of Objects

Recall of the exhibited objects was measured at two points: directly after visiting the exhibition and 3 weeks after visiting the exhibition. Since 29.6% of the participants did not take part in the follow-up, we analyzed the results of both measurement points separately.

Directly After Visiting the Exhibition In the second posttest, we asked the participants to write down all of the objects presented in the first showroom that they could remember. On average, the participants remembered 4.27 (SD = 1.27) out of 6 objects. After controlling for prior knowledge, $F(1{,}157) = 0.45$, $p = 0.505$, $\eta_p^2 < 0.01$, and prior interest, $F(1{,}157) = 1.24$, $p = 0.266$, $\eta_p^2 < 0.01$, we found significant main effects for vision, $F(1{,}157) = 15.40$, $p < .001$, $\eta_p^2 = 0.09$, and haptics, $F(1{,}157) = 13.98$, $p < .001$, $\eta_p^2 = 0.08$. The interaction effect between those two factors was not significant, $F(1{,}157) = 6.96$, $p = .009$, $\eta_p^2 = 0.04$. Subsequent post hoc tests (Tukey's HSD) showed that the participants in the no-objects condition remembered significantly fewer objects than participants in the other conditions, while there were no differences between the other experimental groups (see Fig. 3).

Follow-up In the follow-up survey, we asked the participants again to write down all of the objects presented in the first showroom that they could remember. On average, the participants remembered 3.15 (SD = 1.52) out of 6 objects. After controlling for prior knowledge, $F(1{,}109) = 7.29$, $p < .008$, $\eta_p^2 = 0.06$, and prior interest, $F(1{,}109) = 2.09$, $p = .151$, $\eta_p^2 = 0.02$, we found significant main effects for vision, $F(1{,}109) = 9.52$, $p = .003$, $\eta_p^2 = 0.08$, and haptics, $F(1{,}109) = 27.10$, $p < .001$, $\eta_p^2 = 0.20$, but no significant interaction effect, $F(1{,}109) = 2.98$, $p = .087$, $\eta_p^2 = 0.03$. Post hoc tests (Tukey's HSD) showed that the participants in the no-objects condition remembered significantly fewer objects than the participants in the other conditions and that participants in the only-vision condition remembered significantly fewer objects than the participants in the vision-and-haptics condition. There were no significant differences between the only-haptics and the vision-and-haptics condition and the only-haptics and the only-vision condition (see Fig. 3).

Knowledge Acquisition Test Concerning the First Showroom

The participants were asked to take the test at two measurement points: directly after visiting the exhibition and 3 weeks after visiting the exhibition in the follow-up. Since the questions on

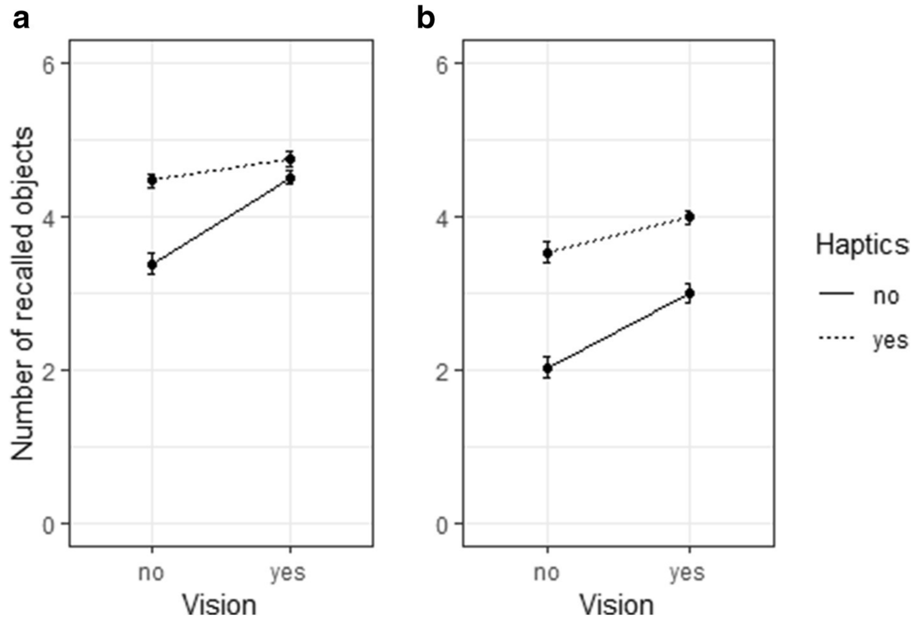

Fig. 3 Scores in the free recall **a** directly after the exhibition and **b** in the follow-up. Error bars represent the standard error

the objects were difficult (virtually impossible) to answer for the no-objects condition, the following analysis was only run for the other three experimental conditions.

Directly After the Exhibition On average, the participants answered 7.36 (SD = 1.70) out of 12 questions correctly. After controlling for prior knowledge, $F(1,115) = 0.01$, $p = .930$, $\eta_p^2 <$ 0.01, prior interest, $F(1,115) = 1.33$, $p = 0.251$, $\eta_p^2 = 0.01$, and the number of objects inspected in the first showroom, $F(1,115) = 4.05$, $p = .047$, $\eta_p^2 = 0.03$, a one-way ANCOVA with the condition (only-haptics, only-vision, vision-and-haptics) as a between-subjects factor revealed a significant main effect, $F(1,115) = 6.89$, $p = .001$, $\eta_p^2 = 0.11$. Post hoc tests (Tukey's HSD) revealed better retention in the haptics-and-vision condition ($M = 7.82$, SD = 1.54) and in the only-vision condition ($M = 7.70$, SD = 1.81) than in the only-haptics condition ($M = 6.62$, SD = 1.53).

Follow-up In the follow-up, the participants answered on average 7.32 (SD = 1.53) out of 12 questions correctly. After controlling for prior knowledge, $F(1,80) = 0.69$, $p = .410$, $\eta_p^2 = 0.01$, prior interest, $F(1,80) = 1.86$, $p = .180$, $\eta_p^2 = 0.02$, and a number of objects inspected in the first showroom, $F(1,80) = 0.46$, $p = .498$, $\eta_p^2 = 0.01$, we found no significant main effect for condition, $F(1, 80) = 5.10$, $p = .008$, $\eta_p^2 = 0.11$.

Second Showroom: Behavior, Interest, and Knowledge Acquisition

The behavior and the outcomes in the second showroom serve as indicators for the participants' motivation to engage themselves with further information on the topic after visiting the first showroom, in which different sensory experiences were available.

Table 3 Means and standard deviations for the duration of stay, number of posters read, and situational interest in the second showroom

	No-objects condition *M* (*SD*)	Only-vision condition *M* (*SD*)	Only-haptics condition *M* (*SD*)	Vision-and-haptics condition *M* (*SD*)
Duration of stay	20.62 (4.78)	21.06 (7.70)	20.59 (5.67)	22.41 (6.05)
Number of posters read	11.86 (0.42)	11.20 (2.23)	11.00 (2.67)	11.56 (1.86)
Situational interest	3.94 (0.66)	3.76 (0.72)	3.68 (0.70)	3.95 (0.50)

Duration of Stay in the Second Showroom

The average duration of stay in the second showroom was just over 20 min ($M = 21.14$, SD = 6.11; see Table 3). Controlling for prior knowledge and prior interest, a two-way ANCOVA with the between-subjects factors vision and haptics showed no significant effects on the duration of stay in the second showroom, all $F < 7.5$.

Number of Posters Read

Most of the participants read all of the posters in the second showroom ($M = 11.04$, SD = 1.99; see Table 3). A two-way ANCOVA with the between-subjects factors vision and haptics, controlling for prior knowledge and prior interest, revealed neither significant differences between the experimental groups nor significant effects of the covariates, all $F < 3.5$.

Situational Interest (Attention Catch and Hold)

After visiting the second showroom, the participants showed a high level of attention catch and hold measured by situational interest ($M = 3.83$, SD = 0.66; see Table 3). After controlling for prior knowledge, $F(1,157) = 0.23$, $p = .630$, $\eta_p^2 < 0.01$, and prior interest, $F(1,157) = 62.22$, $p < .001$, $\eta_p^2 = 0.28$, an ANCOVA showed no significant main effect for vision, $F(1,157) = 0.16$, $p = .687$, $\eta_p^2 < 0.01$, and haptics, $F(1,157) = 0.22$, $p = .638$, $\eta_p^2 < 0.01$, and no significant interaction effect, $F(1,157) = 0.86$, $p = .356$, $\eta_p^2 = 0.01$.

Knowledge Acquisition Test Concerning the Second Showroom

We measured knowledge acquisition at two measurement points: directly after visiting the exhibition and 3 weeks after visiting the exhibition in the follow-up.

Directly After Visiting the Exhibition On average, the participants answered 14.33 (SD = 3.23) out of 20 questions correctly (see Table 4). After controlling for prior knowledge, $F(1,156) = 6.92$, $p = 0.009$, $\eta_p^2 = 0.04$, prior interest, $F(1,156) = 5.29$, $p = .022$, $\eta_p^2 = 0.03$, and a number of posters read in the second showroom, $F(1,156) = 8.76$, $p = .004$, $\eta_p^2 = 0.05$, an ANCOVA showed no significant main effects for vision, $F(1,156) = 0.01$, $p = .912$, $\eta_p^2 < 0.01$, and haptics, $F(1,156) = 0.45$, $p = 0.502$, $\eta_p^2 < 0.01$, and no significant interaction between those factors, $F(1,156) = 2.59$, $p = 0.109$, $\eta_p^2 = 0.02$.

Table 4 Means and standard deviations for the knowledge acquisition test for both measurement points

	No-objects condition *M* (*SD*)	Only-vision condition *M* (*SD*)	Only-haptics condition *M* (*SD*)	Vision-and-haptics condition *M* (*SD*)
After the exhibition	14.83 (2.70)	13.48 (3.67)	13.88 (3.64)	15.15 (2.55)
Follow-up	13.28 (2.95)	12.41 (3.20)	11.69 (3.19)	13.20 (2.98)

Follow-up In the follow-up, the participants answered 12.65 (SD = 3.11) out of questions correctly on average (see Table 4). After controlling for prior knowledge, $F(1,108) = 1.73$, $p = .191$, $\eta_p^2 = 0.02$, prior interest, $F(1,108) = 0.50$, $p = .486$, $\eta_p^2 = 0.01$, and a number of posters read in the second showroom, $F(1,108) = 10.17$, $p = .002$, $\eta_p^2 = 0.09$, an ANCOVA showed no significant main effects for vision, $F(1,108) = 0.38$, $p = .541$, $\eta_p^2 < 0.01$, and haptics, $F(1,108) = 0.54$, $p = .466$, $\eta_p^2 = 0.01$, and no interaction between those factors, $F(1,108) = 1.57$, $p = 0.214$, $\eta_p^2 = 0.01$.

Differences in Affect in Both Showrooms

Both positive and negative affect were measured before the participants visited the exhibition, after visiting the first showroom, and after visiting the second showroom.

Positive Affect A three-way ANOVA with the between-subjects factors vision and haptics and the within factor showroom revealed no significant main effects for the factor vision, $F(1,159) = 0.004$, $p = .952$, $\eta_p^2 < 0.01$, and haptics, $F(1,159) = 0.01$, $p = .910$, $\eta_p^2 < 0.01$, but a significant main effect of the factor showroom, $F(2,318) = 58.38$, $p < .001$, $\eta_p^2 = 0.27$. There was no significant interaction between vision and haptics, $F(1,159) = 0.02$, $p = .902$, $\eta_p^2 < 0.01$, vision and showroom, $F(2,318) = 0.46$, $p = .629$, $\eta_p^2 < 0.01$, and haptics and showroom, $F(2,318) = 0.51$, $p = .599$, $\eta_p^2 < 0.01$. The three-way interaction was not significant, $F(2,318) = 5.74$, $p = .004$, $\eta_p^2 = 0.04$. Means and standard deviations are shown in Table 5.

Negative Affect A three-way ANOVA with the between-subjects factors vision and haptics and the within-subject factor showroom showed no significant main effects for vision, $F(1,159) = 1.74$, $p = .189$, $\eta_p^2 = 0.01$, and haptics, $F(1,159) = 1.23$, $p = .270$, $\eta_p^2 = 0.01$, but a significant main effect for factor showroom, $F(2,318) = 147.24$, $p < .001$, $\eta_p^2 = 0.48$. There was

Table 5 Means and standard deviations for positive and negative affect before visiting the exhibition and after visiting the first and the second showroom

		No-objects condition *M* (*SD*)	Only-vision condition *M* (*SD*)	Only-haptics condition *M* (*SD*)	Vision-and-haptics condition *M* (*SD*)
Positive affect	Before exhibition	3.00 (0.64)	3.19 (0.61)	3.14 (0.61)	3.05 (0.56)
	After showroom 1	2.72 (0.60)	2.68 (0.53)	2.71 (0.46)	2.75 (0.55)
	After showroom 2	2.82 (0.64)	2.67 (0.51)	2.64 (0.64)	2.75 (0.61)
Negative affect	Before exhibition	1.24 (0.36)	1.43 (0.49)	1.35 (0.36)	1.21 (0.29)
	After showroom 1	1.81 (0.59)	1.99 (0.60)	2.12 (0.68)	2.23 (0.84)
	After showroom 2	1.83 (0.69)	2.12 (0.64)	2.00 (0.62)	1.98 (0.76)

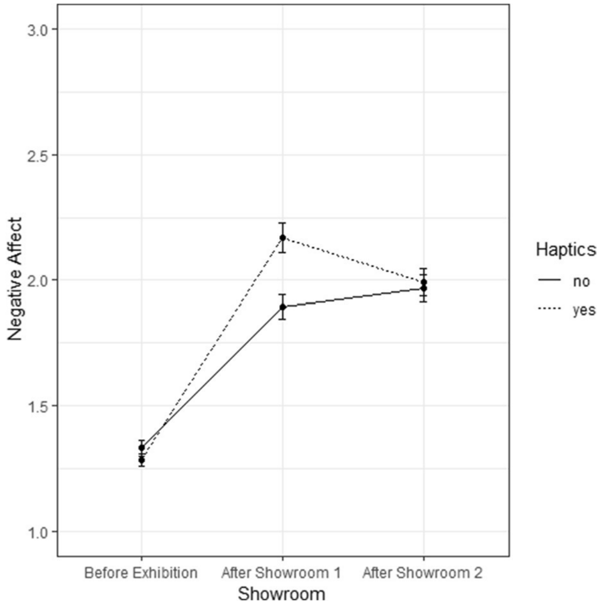

Fig. 4 Interaction effect between the factors haptics and showroom concerning the negative affect (measured on a 5-point Likert-type scale). Error bars represent the standard error

no significant interaction between vision and haptics, $F(1,159) = 2.36$, $p = .126$, $\eta_p^2 = 0.02$, and vision and showroom, $F(2,318) = 0.88$, $p = .416$, $\eta_p^2 = 0.01$, but a significant interaction between haptics and showroom, $F(2,318) = 6.57$, $p = .002$, $\eta_p^2 = 0.04$ (see Fig. 4). Compared with the negative affect before visiting the exhibition, the negative affect increased for all groups after visiting the first showroom. The increase was greater for the participants who were allowed to touch the objects than for the participants who were not allowed to touch them. After visiting the second showroom, there were no group differences in negative affect (see Table 5). There was no significant three-way interaction, $F(2,318) = 1.13$, $p = .324$, $\eta_p^2 = 0.01$.

Discussion

Current theories of embodied cognition posit that the haptic sense complements vision and hearing by a bodily exploration of physical entities in our close surroundings, thus contributing to the formation of enriched mental representations. Haptic exploratory routines constitute an integral part of a human's behavioral repertoire. These routines develop early in childhood and can therefore be considered a privileged type of learning that allows one to acquire biologically primary knowledge in an effortless and intrinsically motivated manner. Furthermore, it has been argued that haptics may support the acquisition of biologically secondary knowledge in educational settings as well (Paas and Sweller 2012). Within the context of multimedia learning, previous research has mainly focused on haptic learning materials specifically designed for instructional purposes, like touchable visualizations or three-dimensional abstract models, demonstrating positive effects on knowledge acquisition (Stull et al. 2018; Tang et al. 2019). According to object-based learning (OBL), haptic exploration of real authentic objects constitutes an additional class of instructional material that should similarly foster knowledge acquisition through processes of embodied cognition but has attracted far less empirical research to date (Chatterjee et al. 2015). To fill this research gap, the present study was set up to investigate whether haptic exploration of real objects, such as tools and artifacts, may serve as an additional channel for enhancing the learning experience and learning outcomes.

Firstly, based on findings from museum settings (Di Franco et al. 2015; Koran et al. 1984; Wilson et al. 2017), it was assumed that the participants would pay more attention to objects if they were given the opportunity for haptic exploration. Contrary to this assumption, we did not find evidence that participants inspected more objects, stayed longer in the first showroom, or reported higher situational interest if they were allowed to touch the exhibited objects. Several aspects may have contributed to the lack of effects of haptics on the participants' attention. In particular, the exhibition's topic of animal husbandry, animal welfare, and nutrition is currently highly debated in Germany. Independent of condition, this may have led both to the observed high rate of inspection of the exhibited objects and to the high scores in self-reported situational interest, while presenting further information via audio guides may have led to a homogenous duration of stay. Nevertheless, it should be kept in mind that both the choice of a current topic and the use of audio explanations reflect conditions that are typical of informal learning settings like exhibitions, thereby achieving a high level of external validity that was aimed at in the present study.

Secondly, referring to Hollins (2010) and Johnson et al. (1989), haptic exploration should serve as an additional input modality to process the learning material and to enrich its mental representation, also easing retrieval in and from the long-term memory. Directly after visiting the whole exhibition, the participants showed a high accuracy of remembered objects as long as they were presented to them in the first showroom either haptically, visually, or in a combination of both. Thus, there was a general advantage of the conditions in which the objects were present over the no-objects condition, indicating that vivid learning material, such as tools and artifacts, supports encoding and retrieval. More importantly, after 3 weeks, the participants who could use their visual and haptic senses during encoding remembered significantly more tools than participants who could only see or neither see nor touch the tools. In addition, there was no difference between the haptics and the vision-and-haptics condition, indicating that the participants who had a haptic experience were able to build a stronger mental representation of the exhibited tools. These results support the findings of Hutmacher and Kuhbandner (2018) that haptic experiences of objects lead to a durable long-term memory representation and also support the findings of Stull et al. (2018) that learning by enacting is stable over a period of several days.

In contrast, the knowledge test showed an advantage of the only-vision condition and the haptics-and-vision condition over the only-haptics condition directly after visiting the exhibition, while in the follow-up no differences between the experimental groups were found. Although the results should be interpreted with care due to the low internal consistency of the knowledge test, this indicates that in the present study haptic exploration did not help to relate additional learning content to the exhibited objects; if anything, the visual channel seems to have been more important in this case. This result stands in contrast to findings from research on finger tracing of printed visualizations and on the manipulation of molecular models, which have both reported positive effects of haptics on learning (Stull et al. 2018; Tang et al. 2019). The main differences to the present study are at least twofold, namely, the character of the learning material and its relationship to the content to be learned. While previous studies used abstract material that was specifically designed for certain instructional purposes and for which the haptic interaction was largely predetermined, the present study relied on authentic artifacts and tools which could be explored freely, as is the typical case in informal learning settings like museums and exhibitions. This unguided mode may have led the participants to apply familiar haptic exploratory routines which are typical for tools and artifacts and which helped them to build an enriched representation of the artifact itself, as evidenced by the memory advantage described above. But although research has demonstrated that such haptic exploratory routines may induce mental simulations of tool use procedures, in the context of the present study, this does not seem to be sufficient to help learners to integrate additional verbal information better than by purely visual inspection of the tools. Thus, contrary to the assumptions of OBL, the present findings indicate that unguided free haptic exploration of authentic objects does not necessarily lead to improved acquisition of additional knowledge about the objects.

In addition, the detrimental effects of the condition of haptic exploration without vision also question the assumption that object manipulation is a kind of biologically privileged process through which humans can acquire knowledge in an effortless way. Instead, the additional processing of haptic information may consume working memory resources. In fact, this may provide an explanation of why the participants in the only-haptics condition showed reduced performance in the knowledge test. Exploring objects in feeler boxes may have drawn the participants' attention to the material qualities of the artifacts, which may have in turn reduced resources for processing the information about objects presented via the audio guide.

Thirdly, based on findings that haptic exploration can lead to higher engagement during the learning process (Di Franco et al. 2015; Roberts et al. 2005; Wilson et al. 2017), we hypothesized that participants who could haptically explore the exhibits will be more motivated to deal with further information on the topic of the exhibition. Contrary to our expectations, we did not find evidence for this transfer of beneficial effects of haptic exploration to the second showroom regarding the duration of stay, the number of posters read, attention catch and hold measured by a situational interest scale, and knowledge acquisition. Independent of condition, most participants tended to inspect all of the posters presented in the second showroom and also reported a high level of situational interest. However, although the mean scores of the knowledge test were in the midrange, showing no floor or ceiling effects, no differences between the conditions were found. Taken together, we could not show that opportunities for haptic exploration support the subsequent acquisition of additional object-related knowledge or enhance the motivation to deal further with the topic.

Finally, based on the findings that affective responses can be evoked by the sensory feedback elicited by the act of touching (Oum et al. 2011; Peck and Shu 2009; Peck and Wiggins 2006; Skolnick 2013), we assumed that the participants who could touch objects in the first showroom will report more intensive affect than the participants who were not allowed to touch the objects. Considering the serious topic of animal welfare, it is not surprising that in all conditions the mood of the participants was not affected positively, but instead negatively by the exhibits. For the first showroom, this increase in negative mood was greater for the participants who could touch the objects than for those who were not allowed to touch them, supporting our hypotheses the haptic exploration will lead the participants to experience more intense affect because they were "touched" more deeply by the topic. After visiting the second showroom, we could not find any group differences in negative affect, but the negative affect remained at a higher level compared with before the visit, indicating that the differences in the first showroom were closely linked to the haptic experience but did not carry over to the second showroom.

Theoretical Implications

Taken together, the results of the present study have important implications both for multimedia learning theories, particularly for the CATLM, and for the role of embodied cognition for processes of knowledge acquisition.

Firstly, while CATLM considers narrations, sounds, texts, and pictures as instructional media, it has not yet considered three-dimensional material objects as a further type of instructional media. The present study showed that providing tools and artifacts that are relevant for the learning topic supports retention, regardless of whether they could be touched or not, indicating that they may serve an important role in multimedia learning environments. Besides real objects, similar effects have also been reported for material models such as chemical molecules (Smith 2016: Stull et al. 2018). Due to the growing possibilities of 3D printing, it is expected that three-dimensional material printouts will play an increasing role as an instructional medium in a broad variety of disciplines (e.g., Smith 2016; Stull et al. 2018). Hence, three-dimensional material objects, such as tools and artifacts, should be added to the list of instructional media in the CATLM.

Secondly, while previous research has focused on the auditory and visual senses, this study gives first indications that the haptic sense constitutes an additional channel to support and improve the learning process. This is not only the case for finger tracing of pictorial learning material (e.g., Agostinho et al. 2015) and manual interaction with three-dimensional models (Stull et al. 2018) but also for handling real objects. However, we only found the advantage of the (additional) haptic channel in the recall of the tools. Factual knowledge, which was reviewed in the knowledge test, was not improved by the haptic exploration, although previous research and theories on tool use and embodied cognition would suggest this. In our study, the linkage between the learning contents and the haptic exploration was perhaps not strong enough, questioning the assumption of OBL that free unguided haptic exploration of real objects is sufficient for increased acquisition of only weakly linked additional information. Instead, in the cited tracing literature (e.g., Agostinho et al. 2015, Du and Zhang 2019; Ginns et al., 2015; Macken and Ginns 2014; Tang et al. 2019), there was a predetermined, guided manual exploration, together with a clear, meaningful connection between the tracing and the learning material. This should also be the case for future studies investigating the role of touching and exploring three-dimensional objects, such as tools and artifacts, on different learning processes. The haptic experience should be directly linked to learning contents, for example, by trying out explained functions of a tool or by giving information on features that can only be haptically explored.

Thirdly, we found evidence that haptic exploration of real objects is effective at different levels of the CATLM: Through haptic exploration, memory processes were improved, and emotions were intensified. However, we did not find evidence that the haptic experience intensified the attention that learners pay to the learning material, helped the learners to relate additional learning content to the exhibited objects, or enhanced the motivation to stay engaged with the learning topic. One important conclusion that can be drawn from this finding is that the multimedia principles of temporal and spatial contiguity (Mayer and Fiorella 2014) also seem to hold for combinations of haptics with other sensory channels. As a consequence, redesigning the present exhibition into one showroom instead of two should increase spatio-temporal contiguity, fostering the development of an integrated representation of the information from the various sources. The findings also raise doubts on the assumption that the haptic exploration of authentic objects can be considered a learning mode that proceeds effortlessly without requiring additional cognitive resources. Therefore, on a more general level, the question arises whether the various well-established principles of multimedia learning apply as well for learning environments that include haptic exploration of authentic objects as part of the learning experience.

Limitations and Conclusions

There are several limitations of the present study that suggest directions for further research. Firstly, in our study, we decided to choose animal husbandry as a learning topic because the acquisition of knowledge of sustainable nutrition and animal welfare is of increasing importance. Nevertheless, the tools used are not neutral objects. They can trigger disgust, rejection, but also interest and curiosity due to the relevance of the topic. The findings show that being confronted with this topic and these tools led to an increase in the negative affect of the participants. Therefore, regarding the generalizability of the present findings, the effects of haptic exploration in the context of a more neutral topic will be necessary.

Secondly, in the context of the present study, it was not possible to collect observational data regarding the participants' touching and viewing behavior without the risk of substantial interference with the naturalistic character of the situation. Therefore, we purposefully decided to confine our research here to asking the participants about viewing and touching immediately after leaving the first showroom. In future studies, video protocols may supplement the participants' reports of their behavior in order to determine in more detail how the visual and/or haptic exploration of the objects took place.

Thirdly, due to the dropout rate in the follow-up questionnaire, our study might be underpowered regarding the follow-up, which means that small effects could not be detected by our analysis. The non-existence of effects should therefore not be overinterpreted. Further research with larger sample sizes is necessary to clarify the question of whether effects are actually not present or whether they could not be found in the present study only because of the data limitations.

Fourthly, given the restricted number of objects inspected in the present study, we also speculate that the beneficial effects of haptic exploration on attention and selection will be more pronounced under conditions of a larger set of real objects or a mixture of objects which can either be haptically explored or are not allowed to be touched.

Apart from these limitations, the present study showed that the haptic exploration of tools did have an impact on how we feel, and what we remember. This enhancement seems to be confined to the immediate haptic experience. Hence, the effects were not found while visiting the second showroom where the haptic experience was not available anymore. This suggests that the effect of haptic exploration is limited to the learning material and situation in which it takes place. Further research is needed to verify these results.

This study does provide theoretical implications for multimedia learning theories, especially on the integration of the haptic channel. But also on a practical level, the results of the present study do have implications for instructional uses of real tangible objects. If relevant information that is helpful for understanding the learning content is transported by the objects themselves, instructors may consider using real objects as authentic learning tools. Nevertheless, the results of the present study do not indicate that real objects may serve as motivators for further engagement with a learning topic.

The present findings are especially important for informal learning settings, like museums and exhibitions. Here, tools, artifacts, and other exhibited objects play a major role, and the preservation and composition in the showroom is a cost- and time-consuming task. The results of our study show that this is a worthwhile effort. In formal education, the findings are also of relevance. Imagine two lessons that differ only in whether or not tools were used for illustration. If a student can at least remember the name of the tools presented, this student has an advantage over a student who does not remember the tools because the former has a clue on what to research in order to catch up on the learning material. But, the results also point out that the uses of haptic exploration of authentic objects should be carefully orchestrated. In particular, although commonplace in informal learning settings, free unguided exploration accompanied by information that is not explicitly linked to the physical qualities of the objects does not seem to make the best out of haptics supported learning. Therefore, the present study should be considered a first step in how to implement haptic exploration of authentic objects in an instructional appropriate manner.

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References

Afonso, A. S., & Gilbert, J. K. (2007). Educational value of different types of exhibits in an interactive science and technology center. *Science Education, 91*(6), 967–987. https://doi.org/10.1002/sce.20220.

Agostinho, S., Tindall-Ford, S., Ginns, P., Howard, S. J., Leahy, W., & Paas, F. (2015). Giving learning a helping hand: Finger tracing of temperature graphs on an iPad. *Educational Psychology Review, 27*(3), 427–443. https://doi.org/10.1007/s10648-015-9315-5.

Baddeley, A. (1992). Working memory. *Science, 255*(5044), 556–559. https://doi.org/10.1126/science.1736359.

Bara, F., & Kaminski, G. (2019). Holding a real object during encoding helps the learning of foreign vocabulary. *Acta Psychologica, 196*, 26–32. https://doi.org/10.1016/j.actpsy.2019.03.008.

Bara, F., Gentaz, E., Colé, P., & Sprenger-Charolles, L. (2004). The visuo-haptic and haptic exploration of letters increases the kindergarten-children's understanding of the alphabetic principle. *Cognitive Development, 19*(3), 433–449. https://doi.org/10.1016/j.cogdev.2004.05.003.

Barsalou, L. W. (2010). Grounded cognition: Past, present, and future. *Topics in Cognitive Science, 2*(4), 716–724. https://doi.org/10.1111/j.1756-8765.2010.01115.x.

Breyer, B., & Bluemke, M. (2016). Deutsche Version der positive and negative Affect Schedule PANAS (GESIS Panel). *Zusammenstellung Sozialwissenschaftlicher Items und Skalen.* https://doi.org/10.6102/zis242.

Chan, M. S., & Black, J. B. (2006). Direct-manipulation animation: Incorporating the haptic channel in the learning process to support middle school students in science learning and mental model acquisition. In*Proceedings of the 7th International Conference of Learning Sciences* (pp. 64–70). Mahwah: LEA.

Chatterjee, H. J., Hannan, L., & Thomson, L. (2015). An introduction to object-based learning and multisensory engagement. In H. J. Chatterjee & L. Hannan (Eds.), *Engaging the senses: Object-based learning in higher education* (pp. 1–18). New York: Routledge.

Dewey, J. (1899). *School and society.* Chicago: Chicago University Press.

Di Franco, P. D. G., Camporesi, C., Galeazzi, F., & Kallmann, M. (2015). 3D printing and immersive visualization for improved perception of ancient artifacts. *Presence Teleoperators and Virtual Environments, 24*(3), 243–265. https://doi.org/10.1162/PRES.

Du, X., & Zhang, Q. (2019). Tracing worked examples: Effects on learning in geometry. *Educational Psychology, 39*(2), 169–187. https://doi.org/10.1080/01443410.2018.1536256.

Etzi, R., Spence, C., Zampini, M., & Gallace, A. (2016). When sandpaper is 'Kiki'and satin is 'Bouba': an exploration of the associations between words, emotional states, and the tactile attributes of everyday materials. *Multisensory Research, 29*(1–3), 133–155. https://doi.org/10.1163/22134808-00002497.

Fiorella, L., & Mayer, R. E. (2016). Eight ways to promote generative learning. *Educational Psychology Review, 28*(4), 717–741. https://doi.org/10.1007/s10648-015-9348-9.

Gallace, A., & Spence, C. (2009). The cognitive and neural correlates of tactile memory. *Psychological Bulletin, 135*(3), 380–406. https://doi.org/10.1037/a0015325.

Geary, D. C. (2008). An evolutionarily informed education science. *Educational Psychologist, 43*(4), 179–195. https://doi.org/10.1080/00461520802392133.

Gibson, J. J. (1966). The senses considered as perceptual systems. Houghton Mifflin.

Gibson, J. J. (1979). The ecological approach to visual perception. Houghton Mifflin.

Ginns, P., Hu, F. T., Byrne, E., & Bobis, J. (2016). Learning by tracing worked examples. *Applied Cognitive Psychology, 30*(2), 160–169. https://doi.org/10.1002/acp.3171.

Glenberg, A. M. (1997). What memory is for. *Behavioral and Brain Sciences, 20*(1), 30–31. https://doi.org/10.1017/S0140525X97360014.

Glenberg, A. M., Witt, J. K., & Metcalfe, J. (2013). From the revolution to embodiment: 25 years of cognitive psychology. *Perspectives on Psychological Science, 8*(5), 573–585. https://doi.org/10.1177/1745691613498098.

Gredlein, J. M., & Bjorklund, D. E. (2005). Sex differences in young children's use of tools in a problem-solving task: The role of object-oriented play. *Human Nature, 16*(2), 211–232.

Grush, R. (2004). The emulation theory of representation: Motor control, imagery, and perception. *The Behavioral and Brain Sciences, 27*(3), 377–442.

Harris, M. A., Peck, R. F., Colton, S., Morris, J., Neto, E. C., & Kallio, J. (2009). A combination of hand-held models and computer imaging programs helps students answer oral questions about molecular structure and function: a controlled investigation of student learning. *CBE Life Sciences Education, 8*(1), 29–43. https://doi.org/10.1187/cbe.08-07-0039.

Harrison, S. J., Hajnal, A., Lopresti-Goodman, S., Isenhower, R. W., & Kinsella-Shaw, K. M. (2011). Perceiving action-relevant properties of tools through dynamic touch: Effects of mass distribution, exploration style , and intention. *Journal of Experimental Psychology: Human Perception and Performance, 37*(1), 193–206. https://doi.org/10.1037/a0020407.

Hidi, S., & Renninger, K. A. (2006). The four-phase model of interest development. *Educational Psychologist, 41*(2), 111–127. https://doi.org/10.1207/s15326985ep4102_4.

Hollins, M. (2010). Somesthetic senses. *Annual Review of Psychology, 61*(1), 243–271. https://doi.org/10.1146/annurev.psych.093008.100419.

Hostetter, A. B., & Alibali, M. W. (2008). Visible embodiment: Gestures as simulated action. *Psychonomic Bulletin & Review, 15*(3), 495–514. https://doi.org/10.3758/PBR.15.3.495.

Hu, F. T., Ginns, P., & Bobis, J. (2015). Getting the point: Tracing worked examples enhances learning. *Learning and Instruction, 35*, 85–93. https://doi.org/10.1016/j.learninstruc.2014.10.002.

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

Johnson, C. J., Paivio, A. U., & Clark, J. M. (1989). Spatial and verbal abilities in children's crossmodal recognition: a dual coding approach. *Canadian Journal of Psychology, 43*(3), 397–412. https://doi.org/10.1037/h0084229.

Kamermans, K. L., Pouw, W., Fassi, L., Aslanidou, A., Paas, F., & Hostetter, A. B. (2019). The role of gesture as simulated action in reinterpretation of mental imagery. *Acta Psychologica, 197*, 131–142. https://doi.org/10.1016/j.actpsy.2019.05.004.

Kaminski, J. A., Sloutsky, V. M., & Heckler, A. (2009). Transfer of mathematical knowledge: The portability of generic instantiations. *Child Development Perspectives, 3*(3), 151–155. https://doi.org/10.1111/j.1750-8606.2009.00096.x.

Knogler, M., Harackiewicz, J. M., Gegenfurtner, A., & Lewalter, D. (2015). How situational is situational interest? Investigating the longitudinal structure of situational interest. *Contemporary Educational Psychology, 43*, 39–50. https://doi.org/10.1016/j.cedpsych.2015.08.004.
Kolb, D. A. (1984). *Experiential learning: Experience as the source of learning and development*. Englewood Cliffs: Prentice Hall.
Koran, J. J., Morrison, L., Lehman, J. R., Koran, M. L., & Gandara, L. (1984). Attention and curiosity in museums. *Journal of Research in Science Teaching, 21*(4), 357–363. https://doi.org/10.1002/tea.3660210403.
Korbach, A., Ginns, P., Brünken, R., & Park, B. (2020). Should learners use their hands for learning? Results from an eye-tracking study. *Journal of Computer Assisted Learning, 36*(1), 102–113. https://doi.org/10.1111/jcal.12396.
Lacey, S., & Sathian, K. (2014). Visuo-haptic multisensory object recognition, categorization, and representation. *Frontiers in Psychology, 5*(730), 1–15. https://doi.org/10.3389/fpsyg.2014.00730.
Lederman, S. J., & Klatzky, R. L. (1987). Hand movements: a window into haptic object recognition. *Cognitive Psychology, 19*(3), 342–368. https://doi.org/10.1016/0010-0285(87)90008-9.
Lederman, S. J., & Klatzky, R. L. (2009). Haptic perception: a tutorial. *Attention, Perception, & Psychophysics, 71*(7), 1439–1459. https://doi.org/10.3758/APP.71.7.1439.
Lewalter, D. (2020). Schülerlaborbesuche aus motivationaler Sicht unter besonderer Berücksichtigung des Interesses. In K. Sommer, J. Wirth, & M. Vanderbeke (Eds.), *Handbuch Forschen im Schülerlabor – Theoretische Grundlagen, empirische Forschungsmethoden und aktuelle Anwendungsgebiete*. Münster: Waxmann-Verlag.
Lewalter, D., & Geyer, C. (2009). Motivationale Aspekte von schulischen Besuchen in naturwissenschaftlich-technischen Museen. *Zeitschrift Fur Erziehungswissenschaft, 12*(1), 28–44. https://doi.org/10.1007/s11618-009-0060-8.
Macken, L., & Ginns, P. (2014). Pointing and tracing gestures may enhance anatomy and physiology learning. *Medical Teacher, 36*(7), 596–601. https://doi.org/10.3109/0142159X.2014.899684.
Manches, A., & Malley, C. O. (2012). Tangibles for learning: a representational analysis of physical manipulation. *Personal and Ubiquitous Computing, 16*(4), 405–419. https://doi.org/10.1007/s00779-011-0406-0.
Mayer, R. E. (2014). Cognitive theory of multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 43–71). Cambridge: Cambridge University Press.
Mayer, R. E., & Moreno, R. (2003). Nine ways to reduce cognitive load in multimedia learning. *Educational Psychologist, 38*(1), 43–52. https://doi.org/10.1207/S15326985EP3801_6.
Mayer, R. E., & Fiorella. (2014). Principles for reducing extraneous processing in multimedia learning: coherence, signaling, redundancy, spatial contiguity, and temporal contiguity principles. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 279–315). Cambridge: Cambridge University Press.
McGuinness, C. (1990). Talking about thinking: The role of metacognition in teaching thinking. In K. Gilhooly, M. Deane, & G. Erdos (Eds.), *Lines of thinking (2)* (pp. 310–312). San Diego: Academic.
Michaels, C. F., Weier, Z., & Harrison, S. J. (2007). Using vision and dynamic touch to perceive the affordances of tools. *Perception, 36*(5), 750–772. https://doi.org/10.1068/p5593.
Minogue, J., & Jones, M. G. (2006). Haptics in education: Exploring an untapped sensory modality. *Review of Educational Research, 76*(3), 317–348. https://doi.org/10.3102/00346543076003317.
Montessori, M. (1912). *The Montessori method*. London: William Heinemann.
Moreno, R., & Mayer, R. (2007). Interactive multimodal learning environments. *Educational Psychology Review, 19*(3), 309–326. https://doi.org/10.1007/s10648-007-9047-2.
Nuszbaum, M., Voss, A., Klauer, K. C., & Betsch, T. (2010). Assessing individual differences in the use of haptic information using a German translation of the Need for Touch Scale. *Social Psychology, 41*(4), 263–274. https://doi.org/10.1027/1864-9335/a000035.
Osiurak, F., & Badets, A. (2016). Tool use and affordance: Manipulation-vased versus reasoning-based approaches. *Psychological Review, 123*(5), 534–568. https://doi.org/10.1037/rev0000027.
Oum, R. E., Lieberman, D., & Aylward, A. (2011). A feel for disgust: Tactile cues to pathogen presence. *Cognition and Emotion, 25*(4), 717–725. https://doi.org/10.1080/02699931.2010.496997.
Paas, F., & Sweller, J. (2012). An evolutionary upgrade of cognitive load theory: Using the human motor system and collaboration to support the learning of complex cognitive tasks. *Educational Psychology Review, 24*(1), 27–45. https://doi.org/10.1007/s10648-011-9179-2.
Paas, F., & Sweller, J. (2014). Implications of cognitive load theory for multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 27–42). Cambridge: Cambridge University Press.
Paivio, A. (1986). *Mental representations: a dual coding approach*. New York: Oxford University Press.

Peck, J., & Childers, T. L. (2003). Individual differences in haptic information processing: The “need for touch” scale. *Journal of Consumer Research, 30*(3), 430–442. https://doi.org/10.1086/378619.

Peck, J., & Shu, S. B. (2009). The effect of mere touch on perceived ownership. *Journal of Consumer Research, 36*(3), 434–447. https://doi.org/10.1086/598614.

Peck, J., & Wiggins, J. (2006). It just feels good: Customers’ affective response to touch and its influence on persuasion. *Journal of Marketing, 70*(4), 56–69. https://doi.org/10.1509/jmkg.70.4.056.

Piaget, J. (1929). *The child's conception of the world*. London: Routledge & Kegan Paul.

Pintrich, P. R. (2003). Motivation and classroom learning. In W. M. Reynolds & G. E. Miller (Eds.), *Handbook of psychology: Educational psychology* (pp. 103–122). New York: Wiley.

Pouw, W. T. J. L., Van Gog, T., & Paas, F. (2014). An embedded and embodied cognition review of instructional manipulatives. *Educational Psychology Review, 26*(1), 51–72. https://doi.org/10.1007/s10648-014-9255-5.

Randler, C., Binngießer, J., & Vollmer, C. (2018). Composite respect for animals scale: Full and brief versions. *Society and Animals, 1*(5-6), 1–21. https://doi.org/10.1163/15685306-12341488.

Remigereau, C., Roy, A., Costini, O., Osiurak, F., Jarry, C., & Le Gall, D. (2016). Involvement of technical reasoning more than functional knowledge in development of tool use in childhood. *Frontiers in Psychology, 7*(1625), 1–11. https://doi.org/10.3389/fpsyg.2016.01625.

Roberts, J. R., Hagedorn, E., Dillenburg, P., Patrick, M., & Herman, T. (2005). Physical models enhance molecular three-dimensional literacy in an introductory biochemistry course. *Biochemistry and Molecular Biology Education, 33*(2), 105–110. https://doi.org/10.1002/bmb.2005.494033022426.

Rowe, S. (2002). The role of objects in active, distributed meaning-making. In S. G. Paris (Ed.), *Perspectives on object-centered learning in museums* (pp. 19–36). New York: Routledge.

Schnotz, W. (2014). An integrated model of text and picture comprehension. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 72–103). Cambridge, MA: Cambridge University Press.

Schwan, S., Grajal, A., & Lewalter, D. (2014). Understanding and engagement in places of science experience: Science museums, science centers, zoos, and aquariums. *Educational Psychologist, 49*(2), 70–85. https://doi.org/10.1080/00461520.2014.917588.

Serrell, B. (1997). Paying attention: The duration and allocation of visitors time in museum exhibitions. *Curator, 40*(2), 108–113. https://doi.org/10.1111/j.2151-6952.1997.tb01292.x.

Sharp, A., Thomson, L., Chatterjee, J., & Hannan, L. (2015). The value of object-based learning within and between higher education disciplines. In H. J. Chatterjee & L. Hannan (Eds.), *Engaging the senses: Object-based learning in higher education* (pp. 97–116). New York: Routledge.

Skolnick, A. J. (2013). Gender differences when touching something gross: Unpleasant? No. Disgusting? Yes! *The Journal of General Psychology, 140*(2), 144–157. https://doi.org/10.1080/00221309.2013.781989.

Skydsgaard, M. A., Møller Andersen, H., & King, H. (2016). Designing museum exhibits that facilitate visitor reflection and discussion. *Museum Management and Curatorship, 31*(1), 48–68. https://doi.org/10.1080/09647775.2015.1117237.

Smith, D. P. (2016). Active learning in the lecture theatre using 3D printed objects. *F1000Research, 5*(61), 1–8. https://doi.org/10.12688/f1000research.7632.1.

Smith, L., & Gasser, M. (2005). The development of embodied cognition: Six lessons from babies. *Artificial Life, 11*(1/2), 13–29. https://doi.org/10.1162/1064546053278973.

Stull, A. T., Gainer, M. J., & Hegarty, M. (2018). Learning by enacting: The role of embodiment in chemistry education. *Learning and Instruction, 55*, 80–92. https://doi.org/10.1016/j.learninstruc.2017.09.008.

Tam, C.-O. (2015). Three cases of using object-based learning with university students: a comparison of the rationales, impact and effectiveness. In H. J. Chatterjee & L. Hannan (Eds.), *Engaging the senses: Object-based learning in higher education* (pp. 117–123). New York: Routledge.

Tang, M., Ginns, P., & Jacobson, M. J. (2019). Tracing enhances recall and transfer of knowledge of the water cycle. *Educational Psychology Review, 31*(2), 439–455. https://doi.org/10.1007/s10648-019-09466-4.

Tulving, E. (1977). Episodic and semantic memory. In E. Tulving & W. Donaldson (Eds.), *Organization of memory* (pp. 381–403). New York: Academic.

Uttal, D. H., O’Doherty, K., Newland, R., Hand, L. L., & DeLoache, J. (2009). Dual representation and the linking of concrete and symbolic representations. *Child Development Perspectives, 3*(3), 156–159. https://doi.org/10.1111/j.1750-8606.2009.00097.x.

Vaesen, K. (2012). The cognitive bases of human tool use. *Behavioral and Brain Sciences, 35*(4), 203–262. https://doi.org/10.1017/S0140525X11001452.

Watson, D., Clark, L. A. L. A., & Tellegen, A. (1988). Development and validation of brief measures of positive and negative affect: The PANAS scales. *Journal of Personality and Social Psychology, 54*(6), 1063–1070. https://doi.org/10.1037/0022-3514.54.6.1063.

Wilson, M. (2002). Six views of emobied cognition. *Psychonomic Bulletin & Review, 9*(4), 625–636.

Wilson, P. F., Stott, J., Warnett, J. M., Attridge, A., Smith, M. P., & Williams, M. A. (2017). Evaluation of touchable 3D-printed replicas in museums. *Curator: The Museum Journal, 60*(4), 445–465. https://doi.org/10.1111/cura.12244.

Yeo, L. M., & Tzeng, Y. T. (2019). Cognitive effect of tracing gesture in the learning from mathematics worked examples. *International Journal of Science and Mathematics Education, 18*(4), 733–751. https://doi.org/10.1007/s10763-019-09987-y.

Zacharia, Z. C. (2015). Examining whether touch sensory feedback is necessary for science learning through experimentation: a literature review of two different lines of research across K-16. *Educational Research Review, 16*, 116–137. https://doi.org/10.1016/j.edurev.2015.10.001.

Appendix C

Study 2

Novak, M., & Schwan, S. (submitted). The effects of touching real objects on learning science-related issues

Abstract

Several theories on learning in multimedia learning environments focus on the visual and auditory access but do not integrate the haptic sense as an additional source of information. In particular, touching three-dimensional objects and the influence of this haptic experience on learning takes mostly a subordinate role. In our study, we investigated how the haptic experience affects learning and learning outcomes. For this purpose, an experimental exhibition on the topic of animal husbandry, breeding, and welfare was designed. In the exhibition, the participants' sensory access to the exhibition objects was systematically varied in a 2 x 2 between-subjects design with the factors vision (yes / no) and haptics (yes / no). Further information about the objects was provided via audio guide and posters. In contrast to the study by Novak & Schwan (2020), and in order to avoid a shift in space and time, the entire exhibition was set up in only one single showroom. To investigate long-term effects of the exhibition, a follow-up survey was conducted after three weeks. Both cognitive and motivational-affective variables were collected. There were mixed results at either level. Overall, the present study does not provide clear evidence that haptic exploration of exhibition objects has a beneficial effect on the reception of the overall exhibition content. That being said, haptic exploration does promote recall of the objects themselves and has a positive effect on the catch component of situational interest. Implications and suggested approaches for further research will be discussed.

Keywords: Haptics, multimedia learning, real tangible objects, spatial and temporal contiguity

The Effects of Touching Real Objects on Learning Science-Related Issues

The current paper is being written during the Covid-19 pandemic – a time in which social distancing is in the spotlight. Shaking hands to welcome business partners, hugging a friend to say goodbye, exploring food and other products while shopping – these are everyday things we try to avoid and which are even forbidden in these times. By strictly avoiding these bodily experiences, we become aware of how central and important they are in our everyday life and how unconsciously they usually occur. While the visual, auditory, and olfactory senses work well from a distance to perceive the environment, under normal circumstances the haptic sense brings us into direct contact with our fellow human beings, objects, and materials. Through touch and different exploratory strategies, we get to know object properties such as shape, size, weight, and surface texture (Lederman & Klatzky, 1987, 2009).

Despite the relevance of the haptic sense for our everyday life, this sensory channel – compared to the visual and auditory sense – has received little attention in research (Gallace & Spence, 2009; Hutmacher, 2019). Although the embodied cognition approach is based on the assumption that cognitive processes are directly related to bodily experiences (e.g., Barsalou, 2010), to date there is a lack of conclusive studies, especially in multimedia learning research, on the question of what role the additional haptic channel can play in learning (Minogue, & Jones, 2006).

The current study attempts to make a contribution to answering the question of what impact real objects and the haptic exploration of these objects does actually have – in combination with the visual and auditory sense – on different aspects of the process of learning science-related issues. To investigate this question, we set up an experimental exhibition on animal husbandry, breeding, and welfare and systematically varied the sensory access of the participants to the exhibition objects. We were interested in cognitive and motivational-affective outcomes. In order to investigate the long-term effects of the exhibition, a follow-up survey was conducted after 3 weeks.

Before we describe our study in more detail, the following sections provide a brief overview of multimedia learning theories, the learning effects of tracing, the role of haptic exploration of three-dimensional objects in learning, and the relevance of spatio-temporal contiguity for relating information from different sensory channels.

Multimedia Learning

In general, multimedia learning environments present information in two or more different ways via various sensory channels, like vision and audition, or via various sign systems, such as texts, pictures, and formulaic notations (Mayer, 2014). Several theories have been proposed that explain learning with multimedia, including the cognitive load theory (CLT) by Sweller and colleagues (Paas & Sweller, 2014), the integrative model of text and picture comprehension by Schnotz (2014), the cognitive theory of multimedia learning (CTML) by Mayer and his colleagues (Mayer, 2014) and the cognitive-affective theory of learning with media (CATLM) by Moreno & Mayer (2007). These approaches focus on various combinations of textual and pictorial material, such as illustrated texts, narrated animations, or virtual realities with text inserts. They are also mainly concerned with the cognitive steps required for the appropriate processing of multimedia learning material, starting from perception and selection of information, its organization, elaboration, and integration in working memory to its transfer into and retrieval from long-term memory.

Although the clear focus of the theories is evident here, a few exceptions can be found. For example, the CATLM explicitly considers the influence of motivational and affective factors and metacognition on learning with multimedia (Moreno & Mayer, 2007). Besides the importance of the auditory and visual channel for access to learning material, tactile, olfactory and gustatory sensory input is regarded as a potential additional source of information that can influence the learning process. (Chan & Black, 2006; Moreno & Mayer, 2007). Thus, CATLM confirms the relevance of using physical media as a means for learning.

In addition, Paas and Sweller (2012) argue that biologically primary knowledge, which requires few working memory resources, can be used to acquire biologically secondary knowledge. As an example, they mention embodied cognition: The use of gestures and object manipulation is seen as primary knowledge that does not need to be explicitly taught but can support the acquisition of secondary knowledge. Therefore, they posit that use of the haptic sense will reduce cognitive load and enhance knowledge acquisition.

Learning Through Tracing

A well-researched example of multimedia learning with a haptic component is tracing, which is a dynamic hand movement on a surface on which a certain shape is traced with the index finger. In Montessori schools, children learn the alphabet using sandpaper letters that they can haptically explore (Montessori, 1912). This teaching technique involves input from several modalities at the same time to explore a letter: Students feel the way the letter is written as they trace its contours, and simultaneously, they see its shape and hear the sound of the letter uttered by their teacher. Bara and colleagues (2004) investigated this teaching technique empirically in an intervention study with French children. The authors found that the additional use of the haptic channel increased the positive effects of the intervention on the decoding skills of the children, on their understanding and use of the alphabetic principle, and on establishing the connection between the orthographic representations of the letters and the phonological representation of the corresponding sounds.

Tracing has also been investigated in multimedia research with a number of scientific learning materials, such as temperature curves (Agostinho et al.,2015), triangle geometry (Ginns et al., 2016), the water cycle (Tang, Ginns, & Jacobson, 2019), or the function of the human heart (Ginns, & Kydd, 2020). These studies show that the haptic exploration have positive effects on knowledge acquisition in the sciences but that there are mixed results regarding cognitive load.

Learning With Objects

Studies on tracing deal with two-dimensional, flat learning material and therefore do not provide any insight into the influence of haptic exploration of three-dimensional objects on learning. Also, multimedia theories do not mention three-dimensional objects or real authentic objects as instructional media. The concept of object-based learning (OBL, Chatterjee, Hannan, & Thomson, 2015; Rowe, 2002), however, provides a different approach in this regard. OBL is based on a multisensory, constructivist approach, and it is assumed that learners develop their knowledge and understanding through the interaction with objects by combining the haptic experience with experiences made through the visual and/or auditory sense.

Several findings from empirical research in science education support OBL's assumptions. Stull, Gainer and Hegarty (2018) investigated the role of enactment with 3D molecular models on learning chemistry. As assumed, students participating in video as well as in classroom lectures learned more if they enacted the demonstration than if they just watched it. Likewise, Smith (2016) showed that 3D printed biological molecules can be used as active learning tools to enhance learning in a lecture hall. Reflecting on their learning with the 3D printed models, the students reported that the models had supported their understanding of the lecture and offered an alternative way of presenting information. Smith attributed the high level of student engagement during the sessions to the use of the 3D printed models. Furthermore, students in a biochemistry course stated that touchable physical models are the preferred and most useful learning tools relative to other types of learning materials (Harris et al., 2009; Roberts et al., 2005).

Whereas these studies have dealt with abstract learning material, Bara and Kaminski (2019) showed that children who – while learning foreign language vocabulary – had the corresponding objects in their hands, learned the words better by heart than those who saw the corresponding pictures of the objects during the learning process. Similarly, Hutmacher and Kuhbandner (2018) found that the haptic exploration of everyday objects can lead to detailed and durable long-term memory representations even in surprise memory tests and in cross-modal memory tests.

A learning setting in which objects and occasionally also the touching of these objects play an important role are museums and exhibitions (Howes, 2014). Koran et al. (1984) showed that a greater number of visitors attended to the exhibits in a gallery when a haptic exploration was allowed compared to purely visual inspection. They also reported higher curiosity and interest. Studies by Di Franco et al (2015) and Wilson et al (2017) found that museum visitors preferred touchable 3D prints and replicas over originals that were not allowed to be touched, as the former allow a haptic experience.

Museums and exhibitions are also a crucial source for science education (Bell et al., 2009, Falk et al., 2007). In a museum visitor study by Novak et al. (2020), differences in the visitors' museum experience and learning were examined when presenting either photos of objects, real objects to look at, or real objects that could both be looked at and be haptically explored in a small exhibition on animal husbandry and animal welfare at the Deutsches Museum in Munich. It was found that the participants who could have a haptic experience remembered more objects and accompanying exhibition topics in a free recall test and perceived higher autonomy than participants in the other two conditions. Contrary to the assumptions, participants in the photo-condition reported higher values for positive and negative affect as well as for situational interest, compared to participants in the other two conditions. Novak and Schwan (2020) set up a similar exhibition in a laboratory setting. This exhibition consisted of two showrooms. In the first showroom, the participants could either touch and see the objects, or only touch, or only see the objects. A fourth group of participants could neither see nor touch the objects. All of the participants received information about the objects via an audio guide. The second showroom presented further information on the topic using posters that were the same for all participants. The authors used a multi-criteria approach with motivational-affective as well as cognitive dependent variables. Among other things, it was found that the haptic experience was beneficial for the recall of the objects both directly after visiting the exhibition and after a delay of three weeks. The effects of the haptic experience in the first showroom could not be transferred to the second showroom; thus, there is no evidence that the haptic experience served as a motivator to engage oneself further with the topic. The authors conclude that it might be important to maintain the spatio-temporal contiguity (Schnotz, 2014) to support the generation of a combined representation of the information from the various sources.

Spatio-Temporal Contiguity of Learning Contents

In the CTL as well as in the CTML, there exist considerations that learning is more effective when different parts of information are presented in an integrated form rather than separately (Schroeder & Cenkci, 2018; Ginns, 2006). In the CLT, this principle is called the split-attention principle and empirical research has supported both spatial and temporal versions of this effect (Ayres & Sweller, 2014). Likewise, the CTML also has a spatial and a temporal version of this effect (Mayer & Fiorella, 2014). The spatial contiguity principle states that learning in a multimedia setting is more effective when words and pictures belonging together are introduced spatially near to rather than far from each other. Analogously, the temporal contiguity principle implies that students learn more profoundly when corresponding learning material is presented simultaneously rather than successively (Mayer & Fiorella, 2014).

Whereas most studies focused on the effects of small distances between text and corresponding illustrations on a single screen (de Koning et al.; 2020; Pouw et al., 2019), reporting only small effects of distance variations, Bauhoff, et al (2012) investigated the integration of information across screens arranged on a 1 m radius hemicycle with inter-screen distances between 30° and 120°. Bauhoff et al. (2012) found that increased distances led to a strategy switch from physical to mental processing, along with an increase in cognitive load. The impact of even larger distances in the course of changing rooms for information was addressed by several studies of Radvansky and colleagues (Radvansky & Copeland, 2006; Radvansky et al., 2011). Speaking of "walking through doorways causes forgetting", they showed that the change of context caused by moving from one room to another led to a decrease in memory for information presented in the room that was left. This finding is of particular relevance for learning material that is spread over two or more rooms, as is typically the case in museums and exhibitions.

The Present Study

The present study used a multi-criteria approach to investigate the influence of haptic exploration of real objects on learning experience and learning outcomes. It was based on an experimental exhibition on the topic "Animal Husbandry, Breeding, and Welfare". In the showroom, the sensory access of the participants to the exhibition objects was systematically varied in a 2 x 2 design with the between-subjects factors vision (yes: objects visible / no: objects not visible) and haptics (yes: objects touchable / no: objects not touchable). An audio guide was used to intensify the multimedia learning experience and to provide information on the functions of the objects.

Based on the assumptions of the CATML and the findings of previous studies (Novak & Schwan, 2020; Novak et al., 2020), we hypothesized that under conditions of high spatio-temporal contiguity, the more sensory channels are used during knowledge acquisition, the more intense the engagement with the learning content should be. Thus, touching and looking at the objects was expected to be better than touching them without vision or looking at them without touching, which in turn should be better than neither seeing nor touching the objects. This should be manifested in

(1) an influence on visit behavior, which should be shown by an increased duration of stay, an increased number of objects and posters inspected, and an increased situational interest;

(2) an increase in memory for the objects and a better performance in a knowledge acquisition test that will take place
    a. directly after the exhibition
    b. in a follow-up;

(3) an intensification of affective states.

Method

Participants

Participants were recruited from our institute's mailing list. They were required to be native German speakers. Assuming medium effect sizes and a power of .95, a power analysis using GPower recommended a sample size of n = 152 participants. We decided to recruit 160 participants (40 per condition). Excluded participants were replaced by other participants. From the 178 recruited participants, 15 had to be excluded because he or she had not followed the instructions properly or because of technical or language difficulties. The remaining 163 participants ranged in age from 18 to 34 years (M = 23.63, SD = 3.00); 127 (77.9 %) were female, 33 (20.2 %) were male and three (1.8 %) were diverse (non-binary). Most of the participants (93.9%) were students from a broad variety of disciplines. The research was approved by the institutional review board of our institute. All of the participants provided written informed consent before participating in this study and were paid for their participation.

Design

We used a 2 x 2 between-subjects design with the factors vision (yes / no) and haptics (yes / no). The participants were randomly assigned to one of the four experimental conditions: no-object-condition (n = 40), only-vision-condition (n = 41), only-haptics-condition (n = 40) and vision-and-haptics-condition (n = 42). Three weeks after visiting the experimental exhibition, the participants were requested to fill out an online survey as a follow-up. A total of 103 participants took part in this follow up (no-object-condition, n = 21; only-vision-condition, n = 29; only-haptics-condition, n = 22; vision-and-haptics-condition, n = 31).

Materials

We set up an exhibition on animal husbandry, breeding, and welfare, including dairy cow and pig farming as well as information on more general topics, such as nutrition, climate, and environment. We used objects, audiotexts, and posters to present the same topic as Novak & Schwan (2020). However, in contrast to Novak & Schwan (2020), the objects were presented together with the posters in one single showroom instead of being presented separately in two showrooms.

Objects. Methods used in conventional dairy cow and pig farming were both demonstrated with the help of three objects, namely, a milking machine, an insemination gun with a veterinary glove, and a dehorning device for cow farming, also a castration forceps, a pig puller, and a heat cutter for pig farming. In the only-vision-condition and the vision-and-haptics-condition, the objects were put on museum pedestals. In the only-haptics-condition, the objects on the pedestals were put into feeler boxes to ensure that the objects could be touched but not seen by the participants. In the no-objects-condition, none of the objects were presented (see Figure 1).

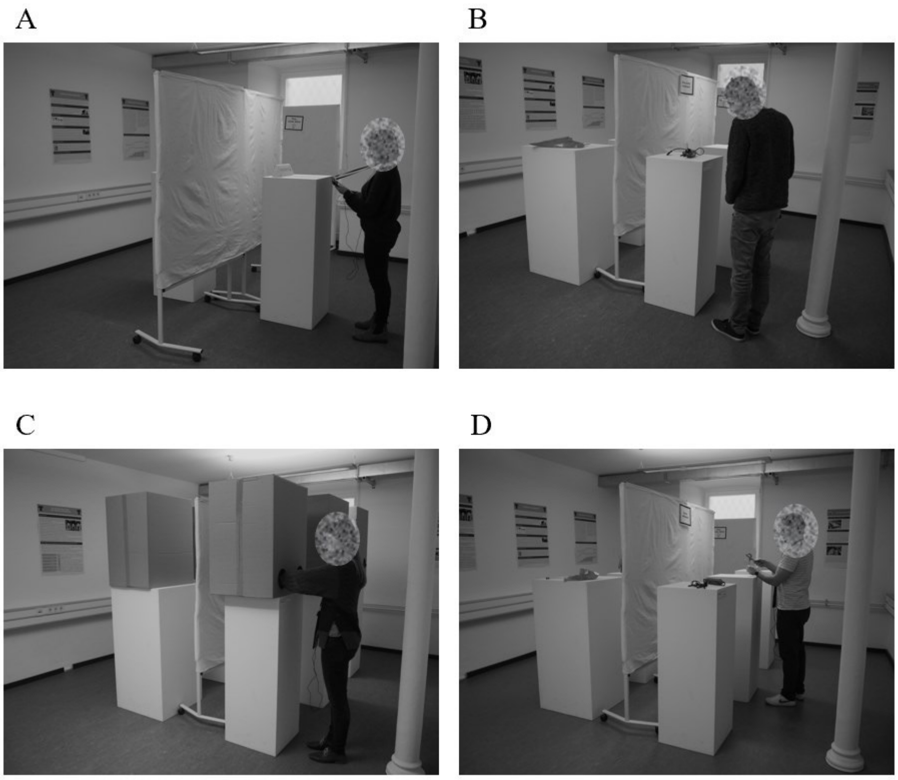

Figure 1. Showroom in the Four Experimental Conditions. (A) no-objects-condition, (B) only-vision-condition, (C) only-haptics-condition, and (D) vision-and-haptics-condition.

Audio Texts. In order to address the auditory channel, all of the participants were provided with information about each exhibit via audio guide. The six audio texts lasted about one minute and twenty seconds each. In the no-objects-condition, we set up two audio stations: one station concerning dairy cow farming that included the audio texts on the milking machine, the insemination gun, and the dehorning device; and one station concerning pig faming consisting of the audio texts on the castration forceps, the pig puller, and the heat cutter for pig farming. The audio texts were the same for each participant.

Posters. For each object, further information on a related topic was provided by posters. The more general topics were also presented by posters. In total, we presented 13 posters which were vividly designed using a combination of texts, illustrations, and diagrams.

Measures

Participants were asked to fill out questionnaires on an iPad mini before and after visiting the exhibition. The follow-up was conducted via an online survey and could be filled out at home. The following scales and tests were used:

Prior Knowledge. Seven items that were answered on a 5-point Likert-type scale (1 “not at all” to 5 “very well”; e.g., “How well are you acquainted with the following topics? – livestock husbandry”). These self-evaluation items measured how good the participants found their knowledge to be on specific aspects of the exhibition’s topic. An average prior knowledge score was calculated from the sum of all responses divided by the total number of items (Cronbach’s $\alpha = .85$).

Prior Interest. Prior thematic interest in the topic of the exhibition were measured by four items on a 5-point Likert-type scale (1 “not at all” to 5 “very”; e. g., “I am interested in the topic of livestock husbandry.”). An average interest score was calculated by the sum of all responses divided by the total number of items (Cronbach’s $\alpha = .83$).

Duration of Stay. The time spent in the exhibition was measured by the iPad mini.

Number of objects inspected and posters read. After visiting the exhibition, we asked the participants to indicate on a plan of the showroom which exhibition contents they had inspected. Two sum scores were calculated: number of objects inspected and number of posters read. In both conditions in which touching was allowed, we asked these participants to indicate whether they had touched the objects in the first showroom. If they had touched fewer than four objects, they were excluded from the analysis. In the only-vision-condition, the participants were asked to indicate whether they had touched the objects. If they had touched more than two objects, they were excluded from the analysis.

Situational interest (attention catch and attention hold). We used an adapted German scale for situational interest (e.g., Lewalter, 2020), which distinguishes between two phases of situational interest: (1) SI-catch, in which the attention and curiosity are aroused. and (2) SI-hold, which describes the desire to maintain attention and spend more time on the contents. Accordingly, the scale included two subscales with six 5-point Likert-type scale items (1 "not at all" to 5 "very much") each for SI-catch (e. g., "The exhibition captivated my attention.") and SI-hold (e. g., "I would like to know more about parts of the exhibition."). For both subscales, the internal consistency was good (Cronbach's α_{catch} = .75, Cronbach's α_{hold} = .83).

Recall of Objects. We asked the participants to list all of the objects that were presented in the exhibition. An answer was considered correct if the participants listed the correct name or if it was clear from the description that the function of the object was understood. A total of six points could be achieved. The rater of the recalled objects was blind to the experimental condition. Ten percent of the answers were randomly chosen and rated by two independent raters. The inter-rater agreement was 100 %.

Description Task. As a form of an extended free recall, we asked the participants to solve the following task for each object: "Please describe in keywords the [milking machine] that you saw in the exhibition with all the features you can remember." The answers were coded by a rater blind to the experimental condition. Ten percent of the answers were randomly chosen and rated by two independent raters. The inter-rater agreement was 93.45%. We analyzed separately the number of correct facts, the number of correct audiotext details, and the number of correct object details. For the "number of correct facts", the participants received one point for each correctly named property of the object (regardless of whether it described the function or not), appearance or texture of the object (e.g., for dehorning device "arbeitet mit Hitze [operates with heat]" or "Wird benutzt um das Verletzungsrisiko der Landwirte zu minimieren [used to minimize the risk of injury to farmers]". No points were given for answers like "Finde ich sinnlos. Gebt den Tieren mehr Platz! [I find it senseless. Give the animals more space!]". For the "number of correct audiotext details", participants earned one point for every fact they learned from the audiotext (e.g., for the heat cutter “Prophylaxe von Schwanzbeißen [Prophylaxis for tail-biting]”). By the “number of correct object details” we mean details that describe the object itself (e.g., for the insemination gun “langes Rohr [long tube]” or for the dehorning device “schwer [heavy]”). Thus, the number of correct audiotext details and the number of correct object details are each subsets of the number of correct facts.

Knowledge Acquisition Test. In the knowledge acquisition test, 16 self-developed multiple-choice questions with four response options (one correct) were asked (e.g., “Approximately how old is a dairy cow when she is inseminated for the first time?” – a) 12 months, b) 16 months, c) 24 months, d) 28 months). The questions addressed the presented posters. We used the knowledge acquisition test in the second posttest and in the follow-up. The internal consistency of the knowledge acquisition test was acceptable (Cronbach’s $\alpha_{\text{After exhibition}} = .73$ and Cronbach’s $\alpha_{\text{Follow-up}} = .62$).

Positive Affect Negative Affect Schedule. A German version of the Positive Affect Negative Affect Schedule (PANAS; Breyer & Bluemke, 2016; Watson, Clark, & Tellegen, 1988) was used to measure the participants’ affective states before and after visiting the exhibition. Both positive and negative affect were measured by ten items on a 5-point Likert-type scale (1 “not at all” to 5 “extremely”). Two average scores (for positive and negative affect) were calculated by the sum of all responses divided by the total number of items (Positive Affect: Cronbach’s $\alpha_{\text{Before Exhibition}} = .83$, Cronbach’s $\alpha_{\text{After Exhibition}} = .78$; Negative Affect: Cronbach’s $\alpha_{\text{Before Exhibition}} = .78$, $\alpha_{\text{After Exhibition}} = .86$).

Need for Touch. We used a German version (Nuszbaum, Voss, Klauer, & Betsch, 2010) of the need for touch (NFT) scale by Peck & Childers (2003) to access the individual preference for haptic information. It consisted of 14 items answered on a 5-point Likert-type scale (1 “not at all” to 5 “very much”; e. g., “When walking through stores, I can’t help touching all kinds of products.”). An average score for the need for touch was calculated by the sum of all responses divided by the total number of items (Cronbach’s $\alpha = .95$).

Procedure

After reading the information about the study and signing the informed consent, the participants were asked to fill out the PANAS, the prior knowledge test, and the prior interest scale. Then they were invited to visit the exhibition and explore it freely at their own pace and interest. Depending on the experimental condition, they were instructed to either touch and explore or not to touch the objects. All of the participants were instructed to use the iPad as an audio guide for each exhibit in the first showroom. Following the visit, the participants were asked to fill out the PANAS and the situational interest scale and to indicate which objects they had inspected and which posters they had read.

After playing cards for about 10 minutes as a filler task, the participants were asked to freely recall all of the objects that were presented in the exhibition and to describe these objects with all features that they could remember. They were also asked to fill out a knowledge acquisition test, the NFT, the CRAS-S, and questions on their sociodemographic data. The study lasted 1 to 1.5 hours for each participant.

After three weeks, the participants were invited by e-mail to fill out the follow-up online survey, which included a self-evaluation of their knowledge and thematic interest, recalling and describing the objects that were presented in the exhibition and again solving the knowledge acquisition test. The completion of the online survey took about 10 minutes.

Results

Differences in Basic Characteristics

The participants reported a medium level of prior knowledge (M = 2.76, SD = 0.60), of prior interest (M = 3.14, SD = 0.78), and a medium score for need for touch (M = 2.59, SD = 0.78). Means and standard deviations for the experimental groups are shown in Table 1.

The two-way ANOVA revealed no significant differences in self-evaluated prior knowledge between the experimental groups, all $F < 2.34$.

The two-way ANOVA with self-evaluated prior interest as a dependent variable revealed no significant main effects of vision, $F(1, 159) = 0.28$, $p = .601$, $\eta_p^2 < 0.01$, and haptics, $F(1, 159) = 0.30$, $p = .583$, $\eta_p^2 < 0.01$, but a significant interaction between those two factors, $F(1, 159) = 10.07$, $p = .002$, $\eta_p^2 = 0.06$. Subsequent post-hoc tests (Tukey-HSD) showed that participants in the vision-and-haptics-condition reported significantly more prior interest than the participants in the only-vision- and only-haptics-condition.

After the exhibition, we measured the participants' need for touch. The two-way ANOVA revealed no significant main effect of vision, $F(1, 159) = 1.14$, $p = .289$, $\eta_p^2 < 0.01$, but a significant main effect of haptics, $F(1, 159) = 7.01$, $p = .009$, $\eta_p^2 = 0.04$. The interaction between those two factors was not significant, $F(1, 159) = 0.25$, $p = .619$, $\eta_p^2 = 0.001$. Subsequent post-hoc tests (Tukey-HSD) showed that participants in the no-objects-condition reported a significant lower score for need for touch than participants in the vision-and haptics-condition. These results may be biased by the haptic experience that only some of the participants had during their visit to the exhibition. However, we purposely chose to assess need for touch after visiting the exhibition to prevent (false) expectations about the exhibition. We only included prior interest as covariate in some of the following analysis.

Table 1

Means and Standard Deviations for Control Variables

	No-objects-condition *M* (*SD*)	Only-vision-condition *M* (*SD*)	Only-haptics-condition *M* (*SD*)	Vision-and-haptics-condi-tion *M* (*SD*)
Need for touch	2.29 (0.79)	2.51 (1.03)	2.73 (0.75)	2.80 (0.90)
Prior knowledge	2.74 (0.49)	2.68 (0.58)	2.69 (0.64)	2.92 (0.66)
Prior interest	3.27 (0.52)	2.95 (0.82)	2.95 (0.87)	3.39 (0.77)

Differences in Visit Behavior

Duration of Stay. The average time spent in the exhibition was barely one half hour (M = 27.93, SD = 8.33). To test whether the groups differed in the time that they spent in the exhibition, we conducted a two-way ANCOVA with the between-subjects factors vision and haptics on duration of stay, controlling for prior interest. There were no significant differences between the experimental groups, all $F < 1.78$. Means and standard deviations are shown in Table 2.

Number of Objects Inspected. Most of the participants dealt with all of the objects and the corresponding audio texts (M = 5.74, SD = 1.11). Since 153 of the 163 participants were engaged with all 6 objects and consequently only 10 people dealt with only 0 to 5 objects, we decided, due to the ceiling effect and the resulting low variance, not to run an inferential statistical analysis here. Means and standard deviations are shown in Table 2.

Number of Posters Read. Most of the participants read nearly all of the 13 presented posters (M = 12.24, SD = 2.13). Similar to the objects inspected, ceiling effects are given as well. 130 participants dealt with all 13 posters, 14 participants with less than 10 posters and 19 participants with 10 to 12 posters. Here, too, we decided against an inference statistical analysis due to the low variance. Means and standard deviations are shown in Table 2.

Table 2

Means and Standard Deviations for Dwell Time, Number of Objects Inspected, and Number of Posters Read.

	No-objects-condition *M* (*SD*)	Only-vision-condition *M* (*SD*)	Only-haptics-condition *M* (*SD*)	Vision-and-haptics-condition *M* (*SD*)
Duration of stay	28.34 (7.28)	26.58 (7.36)	28.66 (9.58)	28.15 (9.02)
Number of objects inspected	5.17 (2.04)	5.83 (0.67)	6.00 (0.00)	5.95 (0.31)
Number of posters read	12.20 (2.30)	12.44 (1.25)	12.53 (1.57)	11.88 (2.97)

Differences in Learning Outcomes

We measured learning outcomes at two measurement points: directly after visiting the exhibition (second posttest) and three weeks after the exhibition. Since 36.81 % of the participants did not take part in the follow-up, we analyzed the results of both measurement points separately.

Knowledge Acquisition Test. The participants answered $M = 10.68$ ($SD = 3.08$) out of 16 questions correctly. The two-way ANOVA with the between-subjects factors vision and haptics revealed no significant differences between the experimental groups, all $F < 0.11$.

In the follow-up, the participants answered $M = 9.51$ ($SD = 2.77$) out of 16 questions correctly. Like in the posttest, there were no significant differences between the experimental groups, all $F < 1.70$. Means and standard deviations are shown in Table 3.

Table 3

Means and Standard Deviations for Knowledge Acquisition Test

	No-objects-condition *M* (*SD*)	Only-vision-condition *M* (*SD*)	Only-haptics-condition *M* (*SD*)	Vision-and-haptics-condition *M* (*SD*)
Posttest	10.07 (2.62)	10.78 (2.74)	10.50 (3.16)	10.74 (3.75)
Follow-Up	10.38 (2.54)	9.24 (2.20)	9.50 (2.72)	9.19 (3.37)

Free Recall. We asked the participants to write down all of the objects presented in the exhibition that they could remember. On average, the participants remembered 4.25 (SD = 1.31) out of 6 objects. A two-way ANOVA showed a significant main effect for vision, $F(1,159) = 17.69$, $p < .001$, $\eta_p^2 = 0.10$, and haptics, $F(1,159) = 8.43$, $p = .004$, $\eta_p^2 = 0.05$. There was also a significant interaction effect between those two factors, $F(1,159) = 8.47$, $p = .009$, $\eta_p^2 = 0.05$. Subsequent post-hoc tests (Tukey-HSD) showed that the participants in the no-objects-condition remembered significantly fewer objects than participants in the other conditions, while there were no differences between the other experimental groups (see Figure 2).

In the follow-up, the participants remembered $M = 3.43$ ($SD = 1.54$) out of 6 objects. A two-way ANOVA showed a significant main effect for vision, $F(1,99) = 6.11$, $p = .015$, $\eta_p^2 = 0.06$, and haptics, $F(1,159) = 8.43$, $p = .005$, $\eta_p^2 = 0.08$. There was no significant interaction effect between those two factors, $F(1,99) = 0.12$, $p = .73$, $\eta_p^2 < 0.01$. Subsequent post-hoc tests (Tukey-HSD) showed that the participants in the no-objects-condition remembered significantly fewer objects than participants in the haptics-and-vision-condition. Group means are illustrated in Figure 2.

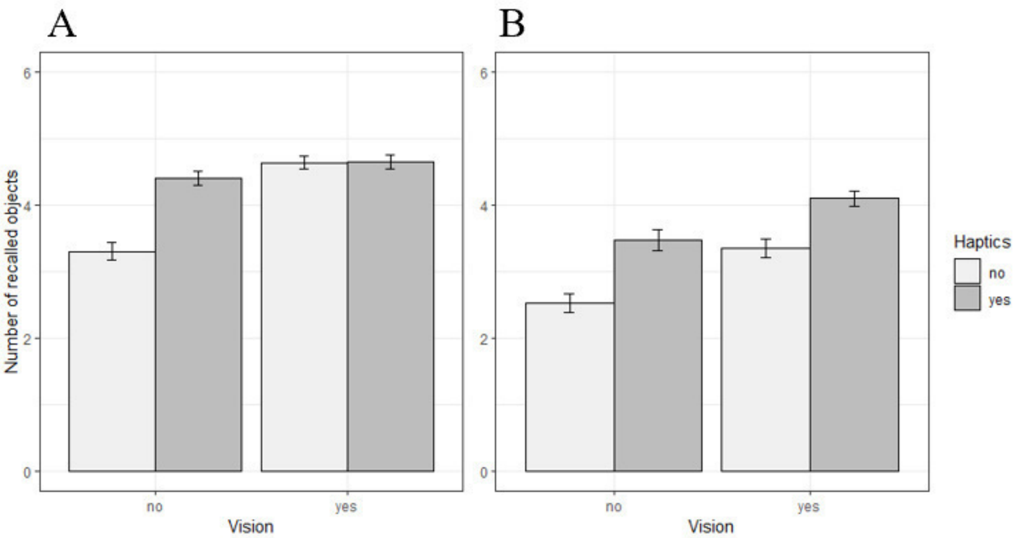

Figure 2. Number of Recalled Objects (A) Directly after the exhibition; (B) in the Follow-up. Error bars represent standard error.

Description Task. In the posttest and in the follow-up, we asked the participants to name all of the features of the presented objects. We analyzed separately the number of correct facts, the number of correct audiotext details, and the number of correct object details.

Posttest. Overall, the participants listed M = 25.1 (SD =9.72) correct facts of the presented objects. After controlling for number of objects inspected, $F(1,158) = 4.55$, $p = .035$, $\eta_p^2 = 0.03$, we found a significant main effect of vision, $F(1,158) = 16.05$, $p < .001$, $\eta_p^2 = 0.09$, and of haptics, $F(1,158) = 6.77$, $p = .010$, $\eta_p^2 = 0.04$. The interaction between those two factors was not significant, $F(1,158) = 4.83$, $p = .363$, $\eta_p^2 < 0.01$. Subsequent post-hoc tests (Tukey-HSD) showed that the participants in the no-objects-condition named significantly fewer facts than participants in the other three conditions. Means and standard deviations are shown in Table 4.

On average, the participants listed M = 15.29 (SD = 8.73) details that they had learned from the audiotext. After controlling for number of objects inspected, $F(1,158) = 0.21$, $p = .651$, $\eta_p^2 < 0.01$, we found a significant main effect of vision, $F(1,158) = 5.00$, $p = .027$, $\eta_p^2 = 0.03$, and of haptics, $F(1,158) = 5.99$, $p = .016$, $\eta_p^2 = 0.04$. Also, the interaction between those two factors was significant, $F(1,158) = 8.14$, $p = .005$, $\eta_p^2 < 0.05$. Subsequent post-hoc tests (Tukey-HSD) showed that the participants in the only-haptics-condition named significantly fewer details from the audiotexts than participants in the other three conditions. Means and standard deviations are shown in Table 4.

Since in the no-objects-condition no objects were presented, the following analysis on the number of listed object details was only run for the other three experimental conditions. Nevertheless, means and standard deviations for all experimental groups are shown in Table 4. The participants listed $M = 12.83$ ($SD = 11.03$) object details (without no-object-condition). We conducted a one-way ANCOVA with exploration type as a between-subjects factor and number of objects inspected as a covariate. There was neither a significant effect of exploration type, $F(2,119) = 1.40$, $p = .250$, $\eta_p^2 = 0.02$, nor of the covariate, $F(1,119) = 2.93$, $p = .089$, $\eta_p^2 = 0.02$.

Follow-up. Overall, the participants listed $M = 12.17$ ($SD = 7.32$) correct facts of the presented objects. After controlling for number of objects inspected, $F(1,98) = 1.88$, $p = .174$, $\eta_p^2 = 0.02$, we found a significant main effect of vision, $F(1,98) = 4.39$, $p = .039$, $\eta_p^2 = 0.04$, but no significant effect of haptics, $F(1,98) = 0.89$, $p = .349$, $\eta_p^2 = 0.01$, and no significant interaction effect, $F(1,98) = 0.44$, $p = .510$, $\eta_p^2 < 0.01$. Means and standard deviations are shown in Table 4.

On average, the participants listed $M = 6.28$ ($SD = 5.35$) details that they had received through the audiotext. After controlling for number of objects inspected, $F(1,98) = 0.34$, $p = .563$, $\eta_p^2 < 0.01$, we found no significant main effect of vision, $F(1,158) = 1.31$, $p = .255$, $\eta_p^2 = 0.01$, but a significant main effect of haptics, $F(1,98) = 10.41$, $p = .002$, $\eta_p^2 = 0.10$. The interaction effect between those two factors was not significant, $F(1,98) = 3.43$, $p = .067$, $\eta_p^2 = 0.03$. Subsequent post-hoc tests (Tukey-HSD) showed that the participants in the only-haptics-condition named significantly fewer details from the audiotexts than participants in the no-objects-condition and the participants in the only-vision-condition. Means and standard deviations are shown in Table 4.

Table 4

Means and Standard Deviations for the Description Task

		No-objects-condition *M* (*SD*)	Only-vision-condition *M* (*SD*)	Only-haptics-condition *M* (*SD*)	Vision-and-haptics-condition *M* (*SD*)
Number of correct facts	Posttest	19.53 (7.41)	26.98 (9.63)	25.03 (9.36)	28.93 (9.91)
	Follow-Up	9.05 (4.70)	13.24 (7.69)	11.73 (7.89)	13.61 (7.67)
Number of audio-text details	Posttest	17.23 (6.72)	16.56 (9.22)	10.38 (7.95)	16.88 (9.17)
	Follow-Up	8.33 (4.51)	7.66 (5.25)	3.00 (4.02)	5.94 (5.84)
Number of object details	Posttest	1.08 (1.73)	11.00 (11.31)	15.03 (9.54)	12.52 (11.93)
	Follow-Up	0.29 (0.64)	5.76 (6.61)	8.82 (6.71)	8.45 (7.05)

As in the posttest, the analysis on number of listed object details was run without the no-objects-condition. After controlling for number of objects inspected, $F(1,78) = 2.86$, $p = .095$, $\eta_p^2 = 0.04$, the one-way ANCOVA showed no significant main effect of exploration type, $F(2,78) = 1.77$, $p = .178$, $\eta_p^2 = 0.04$.

Differences in Motivational-Affective Outcomes

Situational Interest. We measured situational interest directly after visiting the exhibition. We analyzed both subscales – SI-catch and SI-hold separately. The participants reported a relatively high level of SI-catch ($M = 3.91$, $SD = 0.57$). After controlling for prior interest, $F(1,158) = 8.28$, $p = .005$, $\eta_p^2 = 0.05$, a two-way ANCOVA showed no significant main effect of vision, $F(1,158) = 2.21$, $p = .139$, $\eta_p^2 = 0.01$, but a significant main effect of haptics, $F(1,158) = 5.56$, $p = .020$, $\eta_p^2 = 0.03$. Participants with a haptic experience reported a higher SI-catch than participants without a haptic experience. The interaction between those two factors was not significant, $F(1,158) < 0.01$, $p = .995$, $\eta_p^2 < 0.01$. Means and standard deviations are shown in Table 5.

The participants also reported a relatively high level of SI-hold ($M = 3.86$, $SD = 0.65$). After controlling for prior interest, $F(1,158) = 32.20$, $p < .001$, $\eta_p^2 = 0.17$, a two-way ANCOVA showed no significant main effect of vision, $F(1,158) = 3.33$, $p = .070$, $\eta_p^2 = 0.02$, and no significant main effect of haptics, $F(1,158) = 0.80$, $p = .374$, $\eta_p^2 = 0.01$. The interaction between those two factors was not significant, $F(1,158) = 0.12$, $p = .733$, $\eta_p^2 < 0.01$. Means and standard deviations are shown in Table 5.

Table 5

Means and Standard Deviations for Situational Interest.

	No-objects-condition *M* (*SD*)	Only-vision-condition *M* (*SD*)	Only-haptics-condition *M* (*SD*)	Vision-and-haptics-condition *M* (*SD*)
SI-Catch	3.79 (0.61)	3.84 (0.56)	3.92 (0.53)	4.11 (0.54)
SI-Hold	3.81 (0.60)	3.82 (0.57)	3.73 (0.75)	4.06 (0.63)

Positive Affect. Positive Affect was measured before and after visiting the exhibition. A three-way ANOVA with the between-subjects factors vision and haptics and the within-subject factor measurement point revealed no significant main effects for the factor vison, $F(1,159) = 3.182$, $p = .076$, $\eta_p^2 = 0.06$, and haptics, $F(1,159) = 1.40$, $p = .239$, $\eta_p^2 = 0.03$, but a significant main effect of measurement point, $F(1,159) = 59.98$, $p < .001$, $\eta_p^2 = 0.27$. Participants in all experimental groups had a decrease in positive affect after visiting the exhibition. There was no significant interaction between vision and haptics, $F(1,159) = 1.19$, $p = .277$ $\eta_p^2 = 0.02$, vision and measurement point, $F(1,159) = 0.45$, $p = .503$, $\eta_p^2 < 0.01$, and haptics and measurement point, $F(1,159) = 0.35$, $p = .553$, $\eta_p^2 < 0.01$. The three-way interaction was not significant, $F(1,159) = 2.04$, $p = .155$, $\eta_p^2 = 0.01$.

Negative Affect. A three-way ANOVA with the between-subjects factors vision and haptics and the within-subject factor measurement point showed no significant main effects of vison, $F(1,159) = 1.17$, $p = .282$, $\eta_p^2 = 0.01$, and haptics, $F(1,159) = 1.43$, $p = .233$, $\eta_p^2 = 0.02$, but a significant main effect of measurement point, $F(1,159) = 301.87$, $p < .001$, $\eta_p^2 = 0.64$. Negative affect increased after visiting the exhibition. There was neither significant interaction between vision and haptics, $F(1,159) = 0.86$, $p = .36$, $\eta_p^2 = 0.01$, nor between vision and measurement point, $F(1,159) = 0.61$, $p = .436$, $\eta_p^2 < 0.01$, nor between haptics and measurement point, $F(1,159) = 0.44$, $p = .510$, $\eta_p^2 < 0.01$. There was no significant three-way interaction, $F(1,159) < 0.01$, $p = .972$, $\eta_p^2 < 0.01$.

Table 6

Means and Standard Deviations for Positive and Negative Affect

		No-objects-condition *M* (*SD*)	Only-vision-condition *M* (*SD*)	Only-haptics-condition *M* (*SD*)	Vision-and-haptics-condition *M* (*SD*)
Positive affect	Pretest	2.87 (0.55)	3.17 (0.51)	3.08 (0.49)	3.10 (0.60)
	Posttest	2.62 (0.50)	2.74 (0.52)	2.75 (0.56)	2.83 (0.54)
Negative affect	Pretest	1.24 (0.35)	1.21 (0.24)	1.23 (0.21)	1.32 (0.42)
	Posttest	2.02 (0.65)	2.06 (0.58)	2.06 (0.66)	2.23 (0.70)

Discussion

Although theories and empirical research on learning with multimedia has primarily focused on the visual and the auditory channel, there are also theoretical considerations and empirical evidence that the haptic sense can positively influence the learning process - not only on a cognitive but also on a motivational-affective level. The current study investigated the influence of haptic exploration in a science-related, informal learning setting, using a multi-criteria approach. In comparison to a previous study of Novak and Schwan (2020), the aim was to minimize shifts in space and time: The entire learning contents were presented in one single showroom. In the following, we will discuss our findings along different components of the learning process: visit behavior in the experimental exhibition, cognitive outcomes, and motivational-affective outcomes.

Visit Behavior

While research from museum settings (Di Franco et al., 2015; Koran et al., 1984; Wilson et al., 2017) suggests that participants would pay more attention to objects if they had the opportunity for haptic exploration, both studies by Novak & Schwan (2020) and Novak et al. (2020) did not find any differences in visit behavior due to the haptic experience. The current study replicates this finding: The participants spent a lot of time in the experimental exhibition, but there were no differences between the experimental groups. We also found pronounced ceiling effects regarding the number of objects observed and posters read: Nearly all of the participants engaged themselves with all of the provided learning materials. Obviously, when interpreting the results, the specific topic of the exhibition must be considered. The exhibition's topics of animal husbandry, animal welfare and nutrition might be of high interest due to ongoing discussions about it. Additionally, although the presented information was extensive, including thirteen large posters, the number of presented objects was small. Further research should therefore investigate the generalizability of the results for larger exhibits and other exhibition topics.

Learning Outcomes

Findings from research on finger tracing (e.g., Agostinho et al., 2015; Ginns, & Kydd, 2020; Tang, Ginns, & Jacobson, 2019) and on manipulation of molecular models (e.g., Stull et al., 2018; Smith, 2016) indicate positive effects of haptics on science learning. The present study showed mixed results in this respect. In contrast to our assumptions, we could not find differences between the experimental groups in the knowledge acquisition test – neither directly after the exhibition nor in the follow-up. This suggests that factual knowledge that was queried by this type of test was not improved by the haptic experience. When interpreting these results, it is important to bear in mind that the knowledge test included questions about the posters. Thus, the results indicate that the haptic exploration has no influence on the reception of the posters even if there was no change of room as was the case with the study by Novak and Schwan (2020). Maybe the linkage between the learning contents presented by the posters and the haptic experience that could be made by touching the objects was not strong enough to have a positive impact on learning.

In contrast, the free recall results were in line with findings from previous studies. Directly after visiting the exhibition, there was a general advantage of the experimental groups in which the objects were presented over the no-objects-condition: Participants were particularly successful in remembering the objects as long as they were presented to them either haptically, visually, or in combination of both. If the objects were only presented by the audio guide, the participants remembered fewer objects. This suggests that demonstrative learning material supports encoding and retrieval. The results of the follow-up indicate that especially the combination of the visual and haptic sense helps to build a strong mental representation of the exhibited objects, as the difference between the no-objects-condition and the haptics-and-vision-condition was particularly evident.

Additionally, by asking the participants to list all object properties, we wanted to explore what features the participants could remember, what came to mind first, and whether there were differences between the experimental groups. Directly after the exhibition, the participants in the no-objects-condition named significantly fewer facts than participants in the other conditions. This may not be surprising because they did not have any access to the exhibition objects but – as evidenced by the number of remembered audiotext details – they did not name significantly more details that they had received via the auditory channel than the other participants. In this respect, it also appears that people in the only-haptics-condition tended to retrieve less audiotext information than people in the other conditions. They might have been so focused on the impressions of the object itself through the haptic exploration – such as the texture or shape – that the information from the audio text did not come directly to mind. This is reflected at least on a descriptive level with respect to the remembered object details: Here participants named most details in the only-haptics-condition. Of course, this must be interpreted with caution, as no significance was reached. In the follow-up a similar pattern of results was found. It should also be mentioned that regarding the total number of facts named, the visual channel seems to be most important. Given that haptics neither substantially influenced the knowledge test results and memory of object facts nor decreased memory for audio-text information, and only increased memory for object details to a small, non-significant degree, the study did not find positive evidence for the notion that provision of haptics may serve as a source of biologically primary knowledge that may facilitate acquisition of biologically secondary knowledge.

Motivational-Affective Outcomes

Previous studies have shown mixed results regarding situational interest. While Novak & Schwan (2020) did not find any differences in situational interest due to the haptic experience, in the museum study by Novak et al. (2020), participants in the photo condition reported higher values of situational interest than the participants in the touch condition. In the current study, we separately analyzed the two subscales SI-catch and SI-hold. The participants reported relatively high values on both subscales. While there were no differences between the experimental groups in SI-hold, the participants who had been given the opportunity for haptic exploration reported higher values in SI-catch. This suggests that the haptic experience helped to catch the attention of the participants and supported them to initially engage themselves with the topic of our exhibition.

Regarding affect, different results were conceivable. We expected that touching the objects would intensify the affect of our participants: either negative affect due to the nature of the objects that can trigger disgust or rejection or positive affect due to the haptic experience of unknown objects that are not commonplace, or both. In contrast to this expectation, we did not find any differences between the experimental groups – neither in negative nor in positive affect. Nevertheless, we could show that the visit to the experimental exhibition led to an increase in negative and a decrease in positive affect – regardless of the experimental condition.

At the end of our study, we asked the participants what they liked best about our exhibition. In the conditions in which a haptic experience could be made, this haptic experience was repeatedly emphasized:

> Die Ausstellungsobjekte zum Anfassen waren sehr eindrücklich. Gerade weil man diese nicht sehen konnte, sondern nur ertasten, hat man sich ähnlich wehrlos und ängstlich wie die Tiere gefühlt. [**The exhibits to touch were very impressive. Precisely because you could not see them, but only feel them, you felt similarly defenseless and afraid as the animals.]**
> *Participant in the only-haptics-condition*

> Ich fand den Tast-Input sehr hilfreich und interessant, da man damit die Geräte nochmal anders wahrnimmt und sich damit auseinandersetzt. Dazu dann sowohl passendes Audiomaterial und Poster fand ich ganz gut damit man die Info mit so vielen Sinnen wie möglich erfährt. [**I found the touch input very helpful and interesting because you perceive the devices in a different way and deal with it. In addition, both the suitable audio material and posters I found quite good so that one experiences the information with as many senses as possible**.]
> *Participant in the only-haptics-condition*

> Die Kombination aus Lesen, sehen, fühlen und hören. [**The combination of reading, seeing, feeling, and hearing].**
> *Participant in the vision-and-haptics-condition*

> Das Ausstellen der Geräte und die Möglichkeit, sie zu berühren, setzen die ganze Sache in Perspektive und beziehen den Besucher als Verbraucher mit ein, somit besteht keine Möglichkeit mehr, sich geistig von den Praktiken wie künstliche Besamung, Kastration,... zu distanzieren.[**The display of the devices and the possibility to touch them put the whole thing in perspective and engage the visitor as a consumer; thus, there is no**

longer a possibility to mentally distance oneself from the practices such as artificial insemination, castration…]
Participant in the vision-and-haptics-condition

These statements show how impressive and emotionally touching the haptic exploration of objects can be. This was not properly represented by the questionnaires used to record motivational-affective outcomes. Therefore, other methods should be considered in future studies.

Limitations and Conclusions

There are several limitations of the present study that suggest directions for further research. Firstly, it is important to mention that the dropout rate in the follow-up questionnaire was relatively high and unequally distributed across the experimental conditions. The results – especially the non-existence of effects – should therefore be interpreted carefully.

Secondly, the special setting as well as the special topic of our experimental exhibition raise the question of the generalizability of the findings. Of course, we intentionally chose a setting that was as natural as possible and had a high external validity, but further studies are necessary to evaluate the generalizability of the findings. Here, for example, various laboratory studies or exhibitions on other topics and with other objects are conceivable.

In summary, the results of the present study do not show clear evidence that the haptic exploration of the exhibition objects offers an advantage for the reception of the exhibition area. Although the results in the free recall suggest that the presentation of the objects serves to strengthen mental representation, the descriptive task and the knowledge acquisition test could not show that the haptic experience provides an additional benefit. The results are also ambiguous on the behavioral and motivational-affective level. Further research is urgently needed to further explore and understand the influence of haptics on science learning and the learning experience in informal learning contexts. Special attention should be paid to a good linkage between learning materials and haptic experience, as well as an appropriate interrogation of the acquired knowledge. The question of whether haptic exploration is particularly beneficial before, after, or during the presentation of instructional material should also be considered in subsequent research.

References

Agostinho, S., Tindall-Ford, S., Ginns, P., Howard, S. J., Leahy, W., & Paas, F. (2015). Giving learning a helping hand: Finger tracing of temperature graphs on an iPad. *Educational Psychology Review*, *27*(3), 427–443. https://doi.org/10.1007/s10648-015-9315-5

Ayres, P. & Sweller, J. (2014). The split-attention principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 279-315). Cambridge University Press.

Bara, F., Gentaz, E., Colé, P., & Sprenger-Charolles, L. (2004). The visuo-haptic and haptic exploration of letters increases the kindergarten-children's understanding of the alphabetic principle. *Cognitive Development*, *19*(3), 433–449. https://doi.org/10.1016/j.cogdev.2004.05.003

Bara, F., & Kaminski, G. (2019). Holding a real object during encoding helps the learning of foreign vocabulary. *Acta Psychologica*, *196*, 26–32. https://doi.org/10.1016/j.actpsy.2019.03.008

Barsalou, L. W. (2010). Grounded cognition: Past, present, and future. *Topics in Cognitive Science*, *2*(4), 716– 724. https://doi.org/10.1111/j.1756-8765.2010.01115.x.

Bauhoff, V., Huff, M., & Schwan, S. (2012). Distance matters: Spatial contiguity effects as trade-off between gaze switches and memory load. *Applied Cognitive Psychology, 26*(6), 863-871. https://doi.org/10.1002/acp.2887

Bell, P., Lewenstein, B., Shouse, A. W., & Feder, M. A. (2009). *Learning science in informal environments: People, places, and pursuits*. National Academies Press.

Breyer, B., & Bluemke, M. (2016). Deutsche Version der positive and negative Affect Schedule PANAS (GESIS Panel). *Zusammenstellung Sozialwissenschaftlicher Items und Skalen*. https://doi.org/10.6102/zis242

Chan, M. S., & Black, J. B. (2006). Direct-manipulation animation: Incorporating the haptic channel in the learning process to support middle school students in science learning and mental model acquisition. In *Proceedings of the 7th International Conference of Learning Sciences* (pp 64–70). Mahwah, NJ: LEA.

Chatterjee, H. J., Hannan, L., & Thomson, L. (2015). An Introduction to object-based learning and multisensory engagement. In H. J. Chatterjee & L. Hannan (Eds.), *Engaging the senses: Object-based learning in higher education* (pp. 1-18). New York: Routledge.

De Koning, B. B., Rop, G., Pass, F. (2020). Effects of spatial distance on the effectiveness of mental and physical integration strategies in learning from split-attention examples. *Computers in Human Behavior*, *110*, 106379. https://doi.org/10.1016/j.chb.2020.106379

Di Franco, P. D. G., Camporesi, C., Galeazzi, F., & Kallmann, M. (2015). 3D printing and immersive visualization for improved perception of ancient artifacts. *Presence: Teleoperators and Virtual Environments*, *24*(3), 243–265. https://doi.org/10.1162/PRES_a_00229

Falk, J. H., Storksdieck, M., & Dierking, L. D. (2007). Investigating public science interest and understanding: Evidence for the importance of free-choice learning. *Public Understanding of Science*, *16*(4), 455–469. https://doi.org/10.1177/0963662506064240

Gallace, A., & Spence, C. (2009). The cognitive and neural correlates of tactile memory. *Psychological Bulletin, 135*(3), 380–406. https://doi.org/10.1037/a0015325.

Ginns, P. (2006). Integrating information: A meta-analysis of the spatial contiguity and temporal contiguity effects. *Learning and Instruction, 16*, 511–525. https://doi.org/10.1016/j.learninstruc.2006.10.001

Ginns, P., Hu, F. T., Byrne, E., & Bobis, J. (2016). Learning by tracing worked examples. *Applied Cognitive Psychology*, *30*(2), 160–169. https://doi.org/10.1002/acp.3171

Harris, M. A., Peck, R. F., Colton, S., Morris, J., Neto, E. C., & Kallio, J. (2009). A combination of hand-held models and computer imaging programs helps students answer oral questions about molecular structure and function: A controlled investigation of student learning. *CBE - Life Sciences Education*, *8(*1*)*, 29–43. https://doi.org/10.1187/cbe.08-07-0039

Howes, D. (2014). Introduction to sensory museology. *The Senses and Society*, *9*(3), 259–267. https://doi.org/10.2752/174589314X14023847039917

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

Hutmacher, F. (2019). Why is there so much more research on vision than on any other sensory modality? *Frontiers in Psychology, 10,* 1–12. https://doi.org/10.3389/fpsyg.2019.02246

Koran, J.J., Morrison, L., Lehman, J.R, Koran, M.L, & Gandara, L. (1984). Attention and curiosity in museums. *Journal of Research in Science Teaching*, *21*(4), 357-363. https://doi.org/10.1002/tea.3660210403

Lederman, S. J., & Klatzky, R. L. (1987). Hand movements: A window into haptic object recognition. *Cognitive Psychology*, *19*(3), 342–368. https://doi.org/10.1016/0010-0285(87)90008-9

Lederman, S. J., & Klatzky, R. L. (2009). Haptic perception: A tutorial. *Attention, Perception, & Psychophysics*, *71*(7), 1439–1459. https://doi.org/10.3758/APP.71.7.1439

Lewalter, D. (2020). Schülerlaborbesuche aus motivationaler Sicht unter besonderer Berücksichtigung des Interesses. In K. Sommer, J. Wirth, & M. Vanderbeke (Hrsg.), *Handbuch Forschen im Schülerlabor – Theoretische Grundlagen, empirische Forschungsmethoden und aktuelle Anwendungsgebiete (*pp. 63–70). Waxmann-Verlag.

Mayer, R. E. (2014). Cognitive theory of multimedia mearning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 43-71). Cambridge, MA: Cambridge University Press.

Mayer, R. E. & Fiorella, L. (2014). Principles for reducing extraneous processing in multimedia learning: Coherence, signaling, redundancy, spatial contiguity, and temporal contiguity principles. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 279-315). Cambridge, MA: Cambridge University Press.

Montessori, M. (1912). *The Montessori method.* London: William Heinemann.

Minogue, J., & Jones, M. G. (2006). Haptics in education: Exploring an untapped sensory modality. *Review of Educational Research*, *76*(3), 317–348. https://doi.org/10.3102/00346543076003317

Moreno, R., & Mayer, R. (2007). Interactive multimodal learning environments. *Educational Psychology Review*, *19*(3), 309–326. https://doi.org/10.1007/s10648-007-9047-2

Novak, M., & Schwan, S. (2020). Does touching real objects affect learning? *Educational Psychology Review.* https://doi.org/10.1007/s10648-020-09551-z

Novak, M., Phelan, S., Lewalter, D. & Schwan, S. (2020). There is more to touch than meets the eye: Haptic exploration in a science museum. *International Journal of Science Education.* http://dx.doi.org/10.1080/09500693.2020.1849855.

Nuszbaum, M., Voss, A., Klauer, K. C., & Betsch, T. (2010). Assessing individual differences in the use of haptic information using a German translation of the Need for Touch Scale. *Social Psychology, 41*(4), 263–274. https://doi.org/10.1027/1864-9335/a000035

Paas, F., & Sweller, J. (2012). An evolutionary upgrade of cognitive load theory: Using the human motor system and collaboration to support the learning of complex cognitive tasks. *Educational Psychology Review*, *24*(1), 27–45. https://doi.org/10.1007/s10648-011-9179-2

Paas, F. & Sweller, J. (2014). Implications of cognitive load theory for multimedia learning. In R. E. Mayer (Ed.), *The Cambridge Handbook of Multimedia Learning* (pp. 27-42). Cambridge University Press.

Pouw, W., Rop, G., De Koning, B., & Paas, F. (2019). The cognitive basis for the split-attention effect. *Journal of Experimental Psychology: General, 148*, 2058–2075. https://doi.org/10.1037/xge0000578

Radvansky, G. A., & Copeland, D. E. (2006). Walking through doorways causes forgetting: Situation models and experienced space. *Memory & Cognition, 34*(5), 1150-1156.

Radvansky, G. A., Krawietz, S. A., & Tamplin, A. K. (2011). Walking through doorways causes forgetting: Further explorations. *The Quarterly Journal of Experimental Psychology*, 64(8), 1632–1645. https://doi.org/10.1080/17470218.2011.571267

Roberts, J. R., Hagedorn, E., Dillenburg, P., Patrick, M., & Herman, T. (2005). Physical models enhance molecular three-dimensional literacy in an introductory biochemistry course. *Biochemistry and Molecular Biology Education*, *33*(2), 105–110. https://doi.org/10.1002/bmb.2005.494033022426

Rowe, S. (2002). The role of objects in active, distributed meaning-making. In S.G. Paris (Ed.), *Perspectives on object-centered learning in museums* (pp. 19–36). Routledge.

Schnotz, W. (2014). An integrated model of text and picture comprehension. In R. E. Mayer (Ed.), *The Cambridge Handbook of Multimedia Learning* (pp. 72-103). Cambridge University Press.

Schroeder, N. L., & Cenkci, A. T. (2018). Spatial contiguity and spatial split-attention effects in multimedia learning environments: a Meta-Analysis. *Educational Psychology Review, 30*, 679–701.

Smith, D. P. (2016). Active learning in the lecture theatre using 3D printed objects. *F1000Research*, *5*(61), 1–8. https://doi.org/10.12688/f1000research.7632.1

Stull, A. T., Gainer, M. J., & Hegarty, M. (2018). Learning by enacting: The role of embodiment in chemistry education. *Learning and Instruction*, *55*, 80–92. https://doi.org/10.1016/j.learninstruc.2017.09.008

Tang, M., Ginns, P., & Jacobson, M. J. (2019). Tracing enhances recall and transfer of knowledge of the water cycle. *Educational Psychology Review*, *31*(2), 439–455. https://doi.org/10.1007/s10648-019-09466-4

Watson, D., Clark, L. A. L. A., & Tellegen, A. (1988). Development and validation of brief measures of positive and negative affect: the PANAS scales. *Journal of Personality and Social Psychology*, *54*(6), 1063-1070. https://doi.org/10.1037/0022-3514.54.6.1063

Wilson, P. F., Stott, J., Warnett, J. M., Attridge, A., Smith, M. P., & Williams, M. A. (2017). Evaluation of Touchable 3D-Printed Replicas in Museums. *Curator: The Museum Journal*, *60*(4), 445–465. https://doi.org/10.1111/cura.12244

Appendix D

Study 3

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There is more to touch than meets the eye: haptic exploration in a science museum

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There is more to touch than meets the eye: haptic exploration in a science museum

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ABSTRACT

Previous research from in and outside museums suggests that the haptic exploration of surfaces and objects have various educational benefits and can positively influence the museum visit experience. However, there is still a need for more research on the potential effects of object handling on museum learning, especially in science museums. The present study attempts to fill this research gap by investigating differences in museum visitors' science learning when presenting them with photos of objects, real objects, or objects that can be handled. We used a multi-criteria approach in which we examined both cognitive and motivational-affective aspects. We found that the participants who were allowed to haptically explore the exhibition's objects showed a higher recollection of the objects and accompanying text topics and reported a higher perceived autonomy compared to the participants in the other two experimental conditions. Unexpectedly, for situational interest as well as for positive and negative affect, the participants in the photo-condition reported higher values than the participants in the other two conditions. Implications for instructional uses of tangible objects and further directions for research are discussed.

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Object handling; science learning; real objects

In most educational settings, our sense of touch is an underrated and underused sense (Adams, 2015; Jones & Magana, 2015; Minogue & Jones, 2006). It is, however, from our earliest development onwards, an essential part of how we interact and how we explore, perceive, and understand our surroundings (Minogue & Jones, 2006). A distinction is made between two different types of touch: passive and active touch (Gibson, 1962; Jones & Magana, 2015; Loomis & Lederman, 1986; Minogue & Jones, 2006). Passive touch means being touched by a stimulus or a person as in the experience of an object being pressed against the skin. Active touch means that somebody chooses to explore an object manually to gain information about its properties, such as surface texture, temperature, shape, size, and weight (Lederman & Klatzky, 1987, 2009). Minogue and Jones (2006) emphasise that 'the distinction between active and passive touch becomes important when haptics is examined in an educational setting' (p. 332).

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An important instance of active touch is the haptic exploration of objects. From early childhood on, haptic exploratory routines are developed to manually scrutinise objects (Lederman & Klatzky, 1987). Haptic exploration, which is the focus of the present study, does not only allow one to gain information about objects in everyday settings but is also used to foster knowledge acquisition in educational settings.

Engaging multiple senses, including active touch, supports various levels of learning, from acquiring new knowledge to developing critical thinking and improving transferable skills (Chatterjee, 2008; Hannan et al., 2013; Romanek & Lynch, 2008). The handling of objects helps us learn as part of our multimodal system (Smith & Gasser, 2005). By coding and storing memories in different sensory modalities, 'multisensory experiences may lead to richer memories than unisensory experiences' (Gallace & Spence, 2008, p. 174). Following the concept of object-based learning (OBL, Chatterjee et al., 2015; Rowe, 2002), haptic interaction with real objects can serve important roles in the learning process and encourages learners to link these experiences to abstract ideas and concepts (Chatterjee et al., 2015). OBL is based on a multisensory, constructivist approach and goes back to Kolb's experiential learning cycle (1984). By integrating haptics with other senses such as sight and hearing, it is assumed that learners develop their knowledge and understanding through the interaction with objects. Unfortunately, as Minogue and Jones (2006) point out in their review of studies investigating the role of haptics in education, there are still 'formidable barriers to the adoption and widespread use of haptics in education'. There is, however, one educational setting in which touch is increasingly appreciated and required: the science museum (Howes, 2014). Real objects play an important role in museum learning (Chatterjee et al., 2015; Rowe, 2002) and there is some evidence that objects receive more attention and are better remembered than corresponding photographs of objects (Schwan et al., 2016; Snow et al., 2014). Unfortunately, empirical research on the effect of haptic exploration of real objects in the museum context remains scarce. In the present study, we therefore investigated the differences between photos of objects, real objects, and object handling during the museum visit experience. Our leading research question was on how these different (sensory) approaches to the exhibition objects affect the cognitive and motivational-affective characteristics of museum visitors. Before describing our study in more detail, in the following sections, we will introduce a theoretical framework for our study, present benefits of haptic exploration in museums, and give an overview of science learning and the role of touch in science museums.

Theoretical framework: the cognitive-affective theory of learning with media

The haptic sense is far less explored than the visual and auditory senses (Gallace & Spence, 2009; Hutmacher, 2019). This is also reflected in multimedia learning theories, such as the cognitive load theory (CLT, Paas & Sweller, 2014), the integrative model of text and picture comprehension (Schnotz, 2014), the cognitive theory of multimedia learning (CTML, Mayer, 2014) and the cognitive–affective theory of learning with media (CATLM, Moreno & Mayer, 2007). These theories explain the effect of learning with multimedia learning materials, which are often used in museums (Schwan et al., 2018), such as combinations of textual and pictorial material. However, they mostly concentrate on the auditory and visual senses, leaving the haptic sense out. Basically, they consider learning as a constructive process whereby information actively taken in from several sensory channels is processed and elaborated in working memory and then permanently integrated into knowledge structures in long term memory. From here it can be retrieved in future situations. It is further assumed that distributing learning content across several sensory channels (typically the visual and the auditory channel) is beneficial for learning because it reduces working memory's cognitive load and leads to an enriched mental representation of the learning content. While most theories of multimedia learning focus on cognitive steps that are crucial for the comprehension of the multimedia learning material, the CATLM explicitly incorporates the impact of motivational and affective factors and metacognition on learning with multimedia (Moreno & Mayer, 2007). In addition, the CATLM considers tactile, olfactory, and gustatory sensory input as potential additional sources of information – besides the auditory and visual channel – as a way of learning with multimedia. Therefore, it provides an appropriate framework for conceptualising the multifaceted (behavioural, cognitive, and motivational) role of haptic exploration in science learning. This can include several forms of learning material, for example, hands-on elements in Montessori pedagogy (Bara et al., 2004) or in science exhibitions (Afonso & Gilbert, 2007; Skydsgaard et al., 2016), three-dimensional models in chemistry (Smith, 2016; Stull et al., 2018), but also material objects like artifacts and tools (Chatterjee et al., 2015) that are, for instance, displayed in museums. In the next section, we will take a closer look at the potential benefits of haptic exploration in museums.

Haptic exploration in museums

Although early museums were places where objects and artefacts could not only be seen but also touched, held, and 'used', since the nineteenth century, a no-touch policy for visitors has been prevalent in museums around the world (Classen, 2005). Nevertheless, many museum visitors have trouble repressing the urge to use their sense of touch to explore the objects presented to them. Drawing on current observations in an art museum, Classen (2017) describes a wide variety of ways museum visitors still do interact haptically with objects, regardless of whether touching is allowed or not. These 'naturally' occurring haptic explorations range from an inquisitive touch, to a playful, incidental and even defiant touch, just to name a few (Classen, 2017). Thankfully for those museum visitors, we now see a change in museum policy. Artists, exhibit designers, and curators increasingly value and support touching and object handling as an additional means to explore, appreciate, and learn.

A main benefit of touching and handling objects is that it can provide crucial information that remains unknown when museum visitors rely on sight alone. But there is more to touch than meets the eye. Object handling is thought to allow visitors to get a better 'grasp' of the object and its (cultural or scientific) function, significance, and meaning (Rowe, 2002). It can bring objects to life by allowing insight into the way they were developed or are being used in their original setting (Christidou & Pierroux, 2019; Classen, 2017; Howes, 2014). As Spence and Gallace (2008, p. 33) explain: '… many of the objects displayed behind glass in museums and other cultural heritage contexts were originally made in order to be touched, held and/or actively used by people.' Romanek and Lynch (2008) pointed out that handling an object can evoke various emotions, which is in line with results from other fields of research that indicate that haptic exploration can evoke and intensify either positive or negative affective reactions (Etzi et al., 2016; Oum et al., 2011; Peck & Wiggins, 2006; Skolnick, 2013).

There are various ways in which museum visitors can haptically explore objects. Visitors can use (the pressure of) their palms, fingers, or fingertips to trace the shape, to measure the width, to sense the hardness, texture, and shape of an object's surfaces and edges, and to estimate its volume and weight, to name some main examples (Christidou & Pierroux, 2019; Lederman & Klatzky, 1987, 2009). In a study by Koran et al. (1984), there was a significant increase in the number of visitors entering the gallery when the exhibits could be haptically explored compared to only visually inspected. The authors found that when being allowed to touch the exhibits, the visitors reported higher levels of curiosity and interest; thus, a greater number of the visitors attended to the exhibits. Similarly, a qualitative study with semi-structured interviews showed that across a range of disciplines like art, zoology and archaeology, the combination of vision and the haptic sense led to higher levels of engagement and enhanced knowledge and understanding (Sharp et al., 2015). In a case study with 16 students from a Grade 12 biology class, Dohn (2011) investigated how situational interest is developed during a school excursion to an aquarium. Using qualitative methods, such as classroom and field trip observations, video recordings, and interviews, he found that hands-on experiences – along with social involvement, surprise, novelty, and knowledge acquisition– can generate situational interest. He summarises: 'The students experienced it as fun, fascinating, exciting, and interesting, but also a little creepy to handle live fish. The hands-on experience seems closely related to surprise and aha-experience, both at the sensory, tangible level and at the cognitive level.' (p. 16). In addition, hands-on experiences offer further self-determined options for action which, according to the self-determination theory (Ryan & Deci, 2017), are in line with the experience of autonomy as one of the three basic psychological needs relevant for motivation. Along with competence and relatedness, the experience of autonomy needs to be satisfied to promote high-quality forms of self-determined motivation and interest.

Wilson et al. (2017) evaluated the impact of handling 3D printed replicas at the Oxford University Museum of Natural History. The visitors reported that they think that handling 3D printed replicas could enhance the museum experience and their understanding and enjoyment of museum exhibits. They also indicated that they would appreciate it if touchable 3D printed replicas would be presented in more museums and that the opportunity to handle such 3D printed replicas would motivate them to visit more museums. Di Franco et al. (2015) found that museum visitors preferred a replica that can be experienced through touch over an original that can only be looked at.

Taken together, these findings indicate that material objects that can be touched are preferred over objects that can only be looked at; they seem to attract attention, can evoke different emotions, and lead to a higher interest and engagement with the exhibition contents.

Science learning and the role of touch in science museums

Museums and exhibitions are a central source for science learning – for people of all ages (Bell et al., 2009; Falk et al., 2007). Falk and colleagues (2007) point out that 'schools do make an important contribution to public science understanding, however most of the public's science learning is 'extra-curricular', driven by individual needs and interests and achieved through the vehicle of free-choice learning' (p. 464). This quotation addresses the unique characteristics of learning in a (science) museum: free-choice, life-long, and self-paced. Falk and Dierking (2013) explain that 'exhibitions […] allow people to see, ideally even touch, taste, feel, and hear, real things from the real world in an appropriate setting.' (p. 113), leading to unique motivational, affective, and cognitive visitor experiences. The Exploratorium in San Francisco established by Frank Oppenheimer in 1969 was (and is) particularly characterised by a variety of hands-on exhibits, with the aim of using interactive elements to make science tangible (Allen, 2004; Ogawa et al., 2009). The original Exploratorium served as a model for hands-on learning in science centres around the globe (Ogawa et al., 2009). Today, physical interactivity is considered a main characteristic of many science and children's museums (Allen, 2004; Howes, 2014).

Bitgood (1991) distinguishes between three types of 'active response exhibits' (p. 4): (1) simple hands-on exhibits that involve just touching the object; (2) participatory exhibits that involve, for example, comparing the 'feel' of different objects with each other; and (3) interactive exhibits that illustrate a 'cause–effect relationship between the visitor response and a change in the exhibit' (p. 4). While in science centres interactive exhibits play a major role (Afonso & Gilbert, 2007; Allen, 2004), in the present study, we focused on simple hands-on exhibits, hence, the pure effect of touching objects in a science museum. According to Bitgood (1991), simple hands-on exhibits may produce sensory learning, increase the attention on the objects, and enhance interest. Several studies in (formal) science education indicate that learning and understanding can indeed be enhanced by haptic experiences, such as finger tracing or handling three-dimensional molecular models (e.g. Agostinho et al., 2015; Ginns et al., 2016; Smith, 2016; Stull et al., 2018; Tang et al., 2019).

Recently, the role of haptics was investigated in an experimental exhibition on animal husbandry and animal welfare set up in a laboratory setting (Novak & Schwan, 2020). Student participants were led into an exhibition room in which they could either look at exhibits, look at exhibits as well as touch them, touch them but not look at them, or not see or touch any of the objects. In a second exhibition room, they could then freely explore further information (written texts, charts, photographs, and diagrams) about the exhibition's topic. Based on the assumptions of the CATLM, the effects of touching and seeing authentic objects on students' situational interest, affective state, memory, and knowledge gains were investigated immediately after the visit and after a three weeks interval. In line with the CATLM, it was found that haptic exploration fostered memory for the exhibited objects, and also intensified the affective experience of the exhibition. However, haptic exploration did not have an influence on acquiring further knowledge and on becoming more interested in the information presented in the second exhibition room. This study provides some evidence that the haptic exploration of authentic objects may affect learning processes in science exhibitions, but it leaves open the question whether the findings also hold under conditions of authentic museum visitors.

To recapitulate, not only is haptic exploration of museum objects continuously appreciated and practiced by visitors (whether allowed or not), but it is also supported in different types of science museums. But in what ways does object handling impact the museum visit? Can haptic exploration of objects increase key aspects of science learning in the museum context – aspects such as, for example, engagement, interest, visit satisfaction, and an increase in knowledge? Although there is some evidence for the benefits of object handling in museums and of object-based learning in general, this question still remains largely unanswered.

The present study

The previous discussion of the impact of haptic exploration on learning in and outside of museums indicates that object handling in a museum can have a wide range of effects, as specified by the CATLM. The presented studies suggest that haptic exploration can not only support the learning process on a cognitive level but can also enhance the overall museum experience. The present study responds to a call for more research (Hutmacher, 2019; Minogue & Jones, 2006) by investigating the influence of haptic exploration of real objects on learning experiences and learning outcomes in a museum setting. Jones and Magana (2015) state that 'the potential educational uses of haptic tools are still in infancy, but the evidence suggests that haptic learning tools can be enabling in many learning contexts' (p. 332).

Following and extending the study of Novak and Schwan (2020), this study is part of a larger project on the presentation and processing of controversial science topics in exhibitions. It involves the formative evaluation of a new permanent exhibition on agriculture and nutrition currently being designed for and by the Deutsches Museum in Munich. We set up a prototypical part of this exhibition on the subtopic of animal husbandry and animal welfare, which is currently a widely discussed topic. Referring to the CATLM (Moreno & Mayer, 2007), we used a multi-criteria approach and systematically varied the way the exhibition objects were displayed. A comparison was made between the following three groups: (1) object photos, (2) objects that can be visually inspected, and (3) objects that can be visually inspected as well as haptically explored. In this paper, we will address the following questions:

(1) Are there any differences in the visit behaviour between the three experimental groups (measured by the dwell time and engagement with the exhibition contents)? Previous empirical findings indicate that visitors spend more time in front of real objects than object photos and that haptic exploration further increases engagement and time spent in the exhibition (Koran et al., 1984; Schwan et al., 2016; Sharp et al., 2015).
(2) Are there any differences in science learning between the three experimental groups (measured by a free recall of the exhibits and a knowledge acquisition test)? Previous empirical findings indicate that real objects are remembered better than object photos and that touching objects further increases memory (Novak & Schwan, 2020; Schwan et al., 2016). In contrast, evidence for beneficial effects of real objects or of having the opportunity to touch on acquiring further knowledge is mixed at best (Novak & Schwan, 2020; Sharp et al., 2015)
(3) Are there any differences in perceived freedom of choice, situational interest, and affect between the three experimental groups? Previous empirical findings indicate mixed evidence on this issue. While several studies reported increased interest due

to haptic exploration of authentic objects (Dohn, 2011; Koran et al., 1984; Sharp et al., 2015), Novak and Schwan (2020) did find intensified affective states, but no increase in situational interest.

(4) Is object handling appreciated by visitors in the touch-condition? Previous empirical findings indicate that object handling is indeed appreciated by museum visitors (Dohn, 2011; Sharp et al., 2015)

The exhibition

This study is part of a formative evaluation of new permanent exhibition on the topic of agriculture and nutrition in the Deutsches Museum. The mock-up exhibition (Figure 1), designed for the present study, involved a selection of the final exhibition contents on the subtopic of animal husbandry and animal welfare. It included a life-size cow (as eye-catcher), two general, introductory texts (one on animal husbandry, 107 words; the

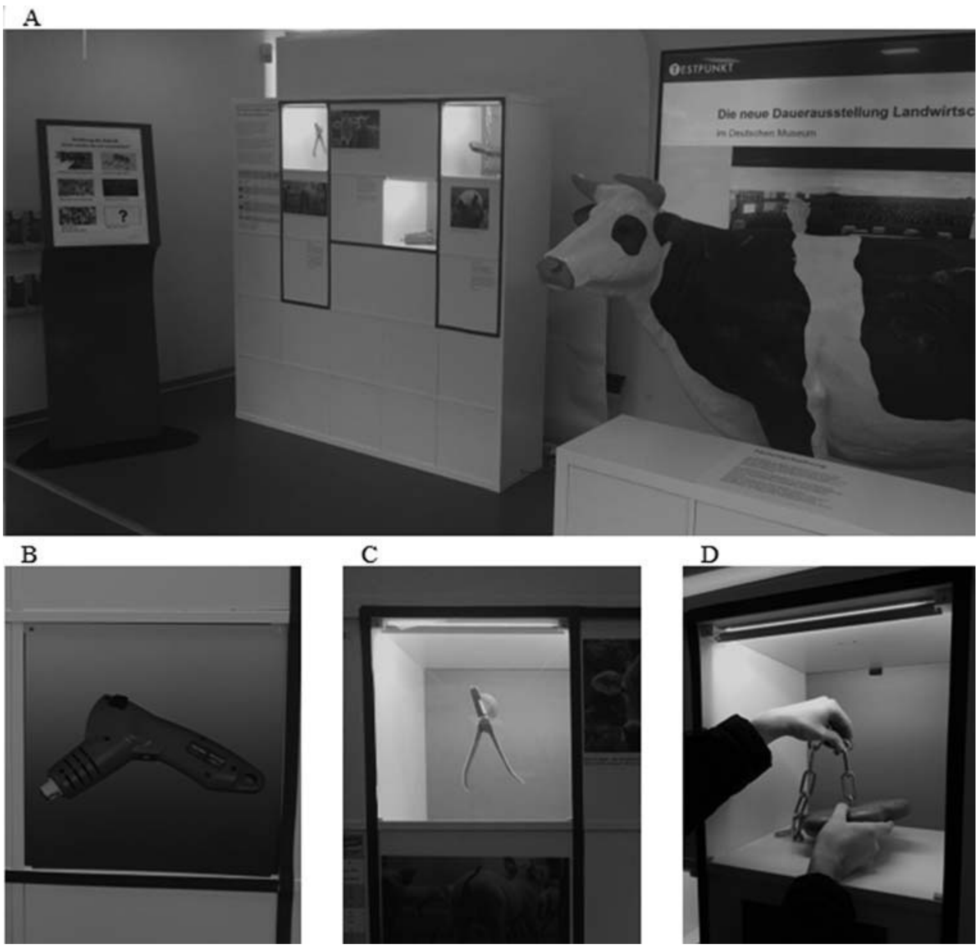

Figure 1. A) Overview of the mock-up exhibition in the vision condition; B) dehorning device in the photo condition C) castration forceps in the vision condition D) pig toy in the touch condition.

other on the co-dependency between consumer, farmer, and animals, 127 words), a chart showing information on product labels and underlying guidelines on animal husbandry, a shelving unit displaying three devices used in animal husbandry with accompanying texts and illustrative photos, and a poster presenting visions for the future. The focus of this study lay on the shelving unit where the following three authentic devices that are currently being used in animal husbandry in Germany were displayed: a castration forceps, a pig toy (i.e. a toy for pigs), and a dehorning device. Each device was presented with an object label, that is, an accompanying text naming and describing the device, its use, and potential consequences for the farmer and the animal (each approximately 85 words), and an animal photo. Depending on the experimental condition, either a photo of each of the devices or the devices themselves were displayed. In the vision condition, a glass pane prevented the devices from being touched. In the touch condition, the participants were able to haptically explore the devices.

The exhibition's design aimed to vividly inform visitors about core issues of animal husbandry and animal welfare. A main learning goal for visitors was to acquire declarative knowledge about concrete tools and procedures involved in animal husbandry, to understand their effects on animal welfare, and to be able to connect this knowledge to the more general aspects of public controversies about animal farming. Depending on the experimental condition, the visitors' experience of the tools differed: In the condition with photographs, experience of the tool was restricted to a realistic depiction that could be explored visually. In the condition with actual objects, visitors additionally experienced an authentic exhibit instead of a media-based representation. In the touch condition, visitors' experience was further enriched by the possibility of haptic exploration, which included not only touching the objects but also allowed for inquisitive haptic exploration, such as holding the tool, feeling its material characteristics, and turning it around. It was assumed that across the three conditions, interaction with the exhibits is increasingly elaborate, resulting in better memory for the exhibits itself as well for additional information related to the tools.

Method

Participants

The study took place at the Deutsches Museum. Museum visitors were recruited as participants before entering the museum while in line to buy tickets. Participants had to be over 18 years of age and had to have very good knowledge of German. Of the 204 recruited participants, 18 had to be excluded because they did not fully follow the procedure of the study or because of language difficulties. The remaining 186 participants ranged in age between 18 and 79 years with an average age of $M = 35.15$ ($SD = 14.14$); 82 of them (44.1%) were female. Overall, the participants had a relatively high level of education: 5.4% had completed a lower secondary education (Hauptschule/Mittelschule/Volksschule), 19.4% an 'intermediate level' of secondary education (Realschule/Mittlere Reife), and 74.8% a higher level of secondary education (Allgemeine Hochschulreife/Fachhochschulreife). All participants provided written informed consent before participating in this study and received a free ticket for the Deutsches Museum for taking part in the study.

Design

We used a one factorial between-subjects design with the factor object display type. While one group of participants could only look at a photograph of the objects, the second group could see the actual objects (placed behind glass). The third group could see, touch, and explore the objects with their hands. The participants were randomly assigned to one of the three experimental conditions: the photo-condition (n = 64), vision-condition (n = 62), and touch-condition (n = 60). The participants were not informed that there were different experimental conditions.

Measures

The participants were asked to fill out a questionnaire before and after visiting the experimental exhibition. Because the present study is part of a large project with different collaborators, we used a broad range of different scales. Referring to the CATLM, we used a multi-criteria approach in which we examined both cognitive and motivational-affective aspects. That said, we will not report all scales used in the study because some of them lie outside of this paper's focus. Data on the participants' point of view of the exhibition's topic (consumer, farmer, animal), their attitude towards the exhibition's topic, and what they think about conventional and organic animal husbandry in general will not be presented. We have, however, made sure we kept a balance of both cognitive and motivational-affective outcome measures. In this paper, we describe and present a mixture of scales and instruments to measure visitors' knowledge and interest before their visit, their visit behaviour, and free recall and a knowledge acquisition test (cognitive outcomes) as well as perceived autonomy, situational interest, PANAS and satisfaction (motivational-affective outcomes) after the visit. In the following section, we will describe these scales, tests, and measurements (see supplemental data for a detailed overview of the instruments).

Measures of basic characteristics

Self-assessed prior knowledge. Eleven items that were answered on a 5-point Likert-type scale (1 'not at all', 2 'hardly', 3 'somewhat', 4 'fairly', 5 'very') measured participants' self-assessed knowledge on specific aspects relating to the exhibition's topic. A main question 'How familiar are you with the following topics?' was followed by 11 broader and more specific topics relevant to the exhibition topic, for example, animal husbandry, the meaning of product labels, and so forth. An average prior knowledge score was calculated from the sum of all responses divided by the total number of items (Cronbach's alpha = .89).

Prior interest. Thematic interest in the topic of the exhibition was measured by four items on a 5-point Likert-type scale (1 'not at all' to 5 'strongly' in agreement with the four statements: e.g. 'I am interested in the topic of livestock husbandry' and 'I like gaining new knowledge on the topic of animal husbandry.'). An average interest score was calculated by the sum of all responses divided by the total number of items (Cronbach's Alpha = .86).

Measures of visit behaviour

Dwell time. The time spent in the experimental exhibition was measured by a neutral observer who was present in the experimental exhibition and wrote down when each participant entered and left the exhibition.

Engagement with the exhibition content. After visiting the experimental exhibition, we asked the participants to indicate on an exhibition plan what they had engaged themselves with. They marked the intensity of their engagement with each of the texts, objects, and pictures on a 5-point Likert-type scale (0 'not at all' to 4 'very'). In the touch condition, they could also indicate whether they had touched the objects. Before starting the data collection, we determined that participants who had touched fewer than two objects were excluded from the analysis (14 participants). Different average engagement scores were calculated by the sum of all responses divided by the total number of items: one score for engagement with the three objects in the exhibition shelf (castration forceps, pig toy, and dehorning device) and one score for the other parts of the exhibition.

Measures of cognitive outcomes

Free recall. With an open-ended question we wanted to examine how well the participants remembered the three objects presented in the shelving unit and described in the accompanying object text (castration forceps, pig toy, and dehorning device). We used the question 'Which objects were used to present which topics in the exhibition?'. The participants earned one point for each device that was correctly named and one point if they described at least one aspect of the accompanying topic (e.g. pig toy - to relieve boredom) correctly. They earned one half point for incomplete answers. A total of 6 points could be achieved. Free recall answers were rated by two independent raters blind to the experimental conditions. The inter-rater agreement was 84.41%. The cases of disagreement were discussed and resolved.

Knowledge acquisition test. Our knowledge acquisition test consisted of 11 self-developed open-ended questions (e.g. 'Why are male piglets castrated?') addressing the all texts (introductory texts, object labels, and other texts, see 'The exhibition' above) that were presented in the exhibition. The participants were instructed to give short answers (keywords only). The participants earned one point for each correct answer. A total of 11 points could be achieved. Two raters, blind to the experimental conditions, individually evaluated the participants' answers and discussed discrepant scores until consensus was reached.

Measures of motivational-affective outcomes

Unless otherwise stated, all motivational-affective outcome variables were answered on a 5-point Likert-type scale (1 'not at all' to 5 'strongly') after visiting the exhibition and the average scores were calculated from the sum of all responses divided by the total number of items.

Perceived autonomy. In the current study, we used the subscale 'Perceived Freedom of Choice' of the German short scale 'Intrinsic Motivation' (Wilde et al., 2009) to measure the participants' perceived autonomy. It involved three items (e.g. 'I was free to direct my own activities in the exhibition.'; Cronbach's Alpha = .90).

Situational interest. Situational interest describes a content-related motivational quality that occurs in a current learning situation and is mainly based on situational factors and how interesting the subject matter is (Knogler et al., 2015; Renninger & Hidi, 2016). It can be theoretically characterised and assessed by focused attention, positive emotion, attribution of personal value, and epistemic orientation (Krapp, 2002), We used an adapted German scale for situational interest (Knogler et al., 2015; Lewalter, 2020) with 12 items, which was developed in the context of science learning in schools and outside of school settings such as museums (e.g. 'The exhibition contents captivated my attention.'; Cronbach's Alpha = .83).

Positive and negative affect scale. The participants' affective states were measured with the German version of the Positive Affect Negative Affect Schedule (PANAS; Breyer & Bluemke, 2016; Watson et al., 1988), which consists of ten items measuring positive (e.g. 'inspired') and ten items measuring negative affect (e.g. 'upset'). The PANAS was measured on a 5-point Likert-type scale (1 'not at all', 2 'a little', 3 'moderately', 4 'quite a bit', 5 'extremely', see Breyer & Bluemke, 2016). Two average scores (for positive and negative affect) were calculated by the sum of all responses divided by the total number of items (Cronbach's $\text{Alpha}_{\text{positive}} = .78$, Cronbach's $\text{Alpha}_{\text{negative}} = .83$).

Satisfaction. The open question 'What did you like most about the exhibition?' served to measure satisfaction. Using a content analysis of the individual answers, the answers were divided into nine different categories: 'increased knowledge/awareness', 'photos', 'texts', 'exhibition topic', 'objects', 'future', 'product labels', 'haptics/interaction', and 'other'. For example, the answer 'Objekte zum Anfassen + Bilder [Objects to touch + pictures]' was classified in the three categories: 'pictures', 'objects', and 'haptics/interaction'. As another example, the answer 'detaillierte Infos über Unterschiede der konventionellen und ökologischen Nutztierhaltung [detailed information on the differences between conventional and organic livestock farming]' was classified in the category 'exhibition topic'. The answers were rated by two independent raters blind to the experimental condition. The inter-rater agreement was 90.27%. The cases of disagreement were rated by a third rater.

Procedure

After reading the information about the study and signing the informed consent, the participants were asked to fill out the pretest questionnaire. The pretest consisted of a self-evaluation of prior knowledge and a prior interest scale. Once completed, the participants were invited to freely explore the mock-up exhibition at their own pace. In the touch condition, the participants were told upon entering the exhibition that they are very welcome to pick up the devices and explore them with their hands. The exhibition contents were the same for all conditions, with the only difference being the object display type. The participants' dwell time was measured by an observer.

Table 1. Means and standard deviations for control variables.

	Photo Condition *M* (*SD*)	Vision Condition *M* (*SD*)	Touch Condition *M* (*SD*)
Prior knowledge	2.83 (0.54)	2.86 (0.78)	2.68 (0.65)
Prior interest	3.39 (0.79)	3.54 (0.88)	3.20 (0.80)

Note. *M* = Mean; *SD* = standard deviation.

Following the visit, the participants were asked to fill out the first part of the posttest questionnaire. They were asked to indicate how intensively they had engaged themselves with each part of the exhibition. After that, they filled out a questionnaire which included scales on perceived choice and situational interest, the PANAS, and an open-ended question on what they liked best about the exhibition. Subsequently, as a filler task, participants were asked to play a type of card game for about 10 min. The card game served as an additional delay and distraction between the exhibition visit and the knowledge assessment tests, which took place in the second part of the posttest.

The second part of the posttest questionnaire contained the free recall question, the knowledge acquisition test, and questions on their sociodemographic data. The study lasted 30–45 min for each participant, depending on the time they had spent in the exhibition.

Results

Differences in basic characteristics

The participants had somewhat high levels of self-assessed prior knowledge ($M = 2.79$, $SD = 0.66$) and prior interest ($M = 3.38$, $SD = 0.83$). To test whether the experimental groups differed in these control variables, we ran a series of one-way ANOVAs with object display type as a between-subjects factor. There were no statistically significant differences in self-assessed prior knowledge and prior interest, both $F < 2.5$, all $p > .05$. Means and standard deviations for the control variables are shown in Table 1.

Differences in visit behaviour

Dwell time

The average dwell time was just over six minutes ($M = 6.19$, $SD = 2.10$). To test whether the groups differed in the time they spent in the experimental exhibition, we conducted a one-way ANOVA with the between-subjects factor object display type. There were no significant differences in the dwell time between the experimental groups, $F(2,183) = 1.469$, $p = .233$, $\eta_p^2 = 0.016$. Means and standard deviations are shown in Table 2.

Engagement with the contents

The participants indicated a somewhat high to fairly high intensity of engagement, regardless of whether we considered the engagement with the objects in the exhibition shelf ($M = 2.75$, $SD = 0.80$) or the engagement with the other parts of the exhibition

Table 2. Means and standard deviations for observation behaviour.

	Photo Condition *M* (*SD*)	Vision Condition *M* (*SD*)	Touch Condition *M* (*SD*)
Dwell time	6.36 (2.39)	6.37 (2.19)	5.81 (1.60)
Engagement with the contents (devices)	2.60 (0.95)	2.74 (0.76)	2.93 (0.60)
Engagement with the contents (other parts)	2.92 (0.63)	2.87 (0.51)	2.98 (0.56)

Note. *M* = Mean; *SD* = standard deviation. Engagement with the contents ranged from 0 to 4.

($M = 2.92$, $SD = 0.56$). On a descriptive level, engagement with the objects was highest in the touch condition (see Table 2). However, the one-way ANOVA did not reach significance, $F(2,\ 183) = 2.590$, $p = 0.078$, $\eta_p^2 = 0.028$. Further, there were no differences in engagement scores between the experimental groups concerning the other parts of the exhibition, $F(2,\ 182) = 0.655$, $p = 0.521$, $\eta_p^2 = 0.007$.

Differences in cognitive outcomes

Free recall

Participants achieved an average free recall score of $M = 3.04$ ($SD = 1.47$) out of a maximum score of 6 points. Means and standard deviations are shown in Table 3. There was a significant difference between groups as determined by a one-way ANOVA, $F(2,183) = 22.605$, $p < .001$, $\eta_p^2 = .198$. A Tukey post-hoc test revealed that the participants in the photo condition had a statistically significant lower score than the participants in the touch condition ($p < .001$) and the participants in the vision condition ($p = .001$). The participants in the vision-condition had a statistically significant lower score than the participants in the touch condition ($p = .011$). The differences between the experimental groups are illustrated in Figure 2.

Knowledge acquisition

On average, the participants answered $M = 8.66$ ($SD = 1.94$) out of 11 questions correctly. There was a significant difference between groups as determined by a one-way ANOVA, $F(2,\ 181) = 3.357$, $p = .037$, $\eta_p^2 = .036$. On a descriptive level, the participants in the vision condition and the participants in the touch condition seem to be better than participants in the photo condition (see Table 3). However, a Tukey post-hoc test revealed neither a significant difference between the photo condition and the vision condition ($p = .051$) nor between the photo condition and the touch condition ($p = .093$) nor between the vision condition and the touch condition ($p = .968$).

Table 3. Means and standard deviations for cognitive outcomes.

	Photo Condition *M* (*SD*)	Vision Condition *M* (*SD*)	Touch Condition *M* (*SD*)
Free recall	2.22 (1.29)	3.12 (1.35)	3.83 (1.35)
Knowledge acquisition	8.16 (2.33)	8.97 (1.92)	8.88 (1.33)

Note. *M* = Mean; *SD* = standard deviation. The maximum score for free recall was 6 points and for the knowledge acquisition test 11 points.

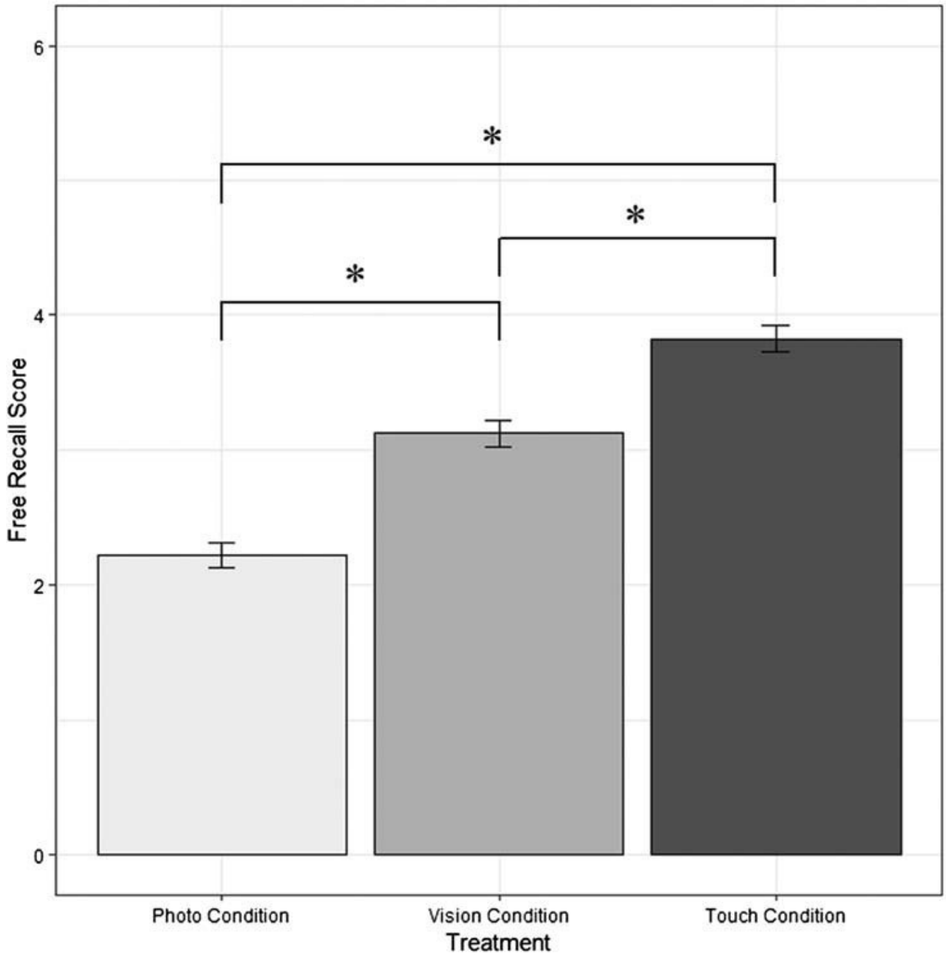

Figure 2. Scores in the Free Recall for the Three Experimental Conditions. Error bars represent the standard error.

Differences in motivational-affective outcomes

Perceived autonomy

The participants reported an average level of $M = 3.83$ ($SD = 1.09$) on the 5-point Likert-type scale assessing their perceived autonomy when visiting the experimental exhibition. There was a significant difference between groups as determined by a one-way ANOVA, $F(2, 180) = 5.907$, $p = .003$, $\eta_p^2 = .062$. A Tukey post-hoc test revealed that the participants in the photo condition ($p = .021$) and the participants in the vision condition ($p = .005$) had a statistically significant lower score than the participants in the touch condition. There was no statistically significant difference between the photo condition and the vision condition ($p = .833$). Means and standard deviations are shown in Table 4.

Table 4. Means and standard deviations for perceived freedom of choice, situational interest, and affect.

	Photo Condition *M* (*SD*)	Vision Condition *M* (*SD*)	Touch Condition *M* (*SD*)
Perceived autonomy	3.70 (1.10)	3.59 (1.21)	4.21 (0.83)
Situational interest	4.02 (0.52)	3.88 (0.51)	3.78 (0.52)
Negative Affect	2.25 (0.62)	1.95 (0.61)	1.94 (0.68)
Positive Affect	2.75 (0.59)	2.66 (0.59)	2.46 (0.50)

Note. *M* = Mean; *SD* = standard deviation. Perceived autonomy, situational interest, negative affect, and positive affect ranged from 1 to 5.

Situational interest

The participants reported an average level of $M = 3.90$ ($SD = 0.53$) on the 5-point Likert-type scale assessing their situational interest when visiting the experimental exhibition. A one-way ANOVA showed significant differences between the experimental groups, $F(2, 182) = 3.600$, $p = .029$, $\eta_p^2 = 0.038$. A Tukey post-hoc test revealed that the participants in the photo condition reported a higher situational interest than the participants in the touch condition ($p = .022$). There were neither statistically significant differences between the photo condition and the vision condition ($p = .281$) nor between the vision condition and the touch condition ($p = .493$). Means and standard deviations are shown in Table 4.

Positive and negative affect scale (PANAS)

On average, the participants reported on a 5-point Likert-type scale ‘a little’ negative affect after visiting the exhibition ($M = 2.05$, $SD = 0.65$). A one-way ANOVA determined significant differences between the groups, $F(2, 182) = 4.713$, $p = .010$, $\eta_p^2 = 0.049$. A Tukey post-hoc test revealed that the participants in the photo condition had a higher score of negative affect than the participants in the vision condition ($p = .025$) and the participants in the touch condition ($p = .023$). There was no statistically significant difference between the vision and the touch condition ($p = .999$).

On average, after visiting the exhibition participants reported between ‘a little’ positive affect to a moderate level of positive affect on a 5-point Likert-type scale ($M = 2.63$, $SD = 0.57$). There was a significant difference between groups as determined by a one-way ANOVA, $F(2, 182) = 4.420$, $p = .013$, $\eta_p^2 = 0.046$. A Tukey post-hoc test revealed that the participants in the photo condition had a higher score of positive affect than the participants in the touch condition ($p = .011$). There were neither statistically significant differences between the photo condition and the vision condition ($p = .656$) nor between the vision condition and the touch condition ($p = .112$). Means and standard deviations are shown in Table 4.

Satisfaction

As part of the post-questionnaire, the participants also answered an open question on what they liked best about the exhibition. The individual answers given by our participants ($n = 186$) could be grouped into nine different categories: ‘increased knowledge/awareness’, ‘photos’, ‘texts’, ‘exhibition topic’, ‘objects’, ‘future’, ‘product labels’, ‘haptics/interaction’, and ‘other’. Due to the focus of the study, we were particularly interested in the number of visitors mentioning haptic exploration as the best thing about the exhibition, bearing in mind only those in the touch condition ($n = 60$) were able to handle objects. In fact, 24 out of 60 participants (40%) liked the haptic experience best at the exhibition. This category was named second most frequently in the touch condition (after 'objects' which was mentioned by 27 participants). In addition, one person from another condition indicated that they would have liked to have been able to touch the exhibits.

Discussion

Although there is some evidence from in and outside museums that haptic exploration can enrich the overall visit experience (including the visitors' learning process), systematic research on the effects of object handling in museums remains scarce. The present study attempts to fill this research gap by investigating differences in museum visitors' science learning when presenting them with photos of objects, real objects, or objects that can be handled. Based on the CATLM, we investigated the effects of haptic exploration on visitors' cognitive, motivational, and affective states. We found that the participants who were allowed to haptically explore objects reported a higher perceived autonomy and showed a higher recollection of the exhibition's objects and accompanying text topics compared to the participants in the other two groups. Surprisingly, we found that participants in the photo condition had higher scores in situational interest as well as in negative and positive affect. In the following, we will discuss our findings on the role of haptics along different components of the museum visit: visit behaviour, cognitive outcomes, motivation and affect, and visitor satisfaction.

Visit behaviour

Christidou and Pierroux (2019, p. 16) found that object handling 'fostered longer and deeper object-related enquiries' in an art museum; however, in our study there were no significant differences between the experimental groups in the dwell time nor in the intensity of engagement with the contents. This may be because our mock-up exhibition was small, not allowing for a large variation in the dwell time. Additionally, although visitors in the touch condition reported a slightly higher level of engagement than the other two groups, we found no significant differences. This could be due to the fact that the participants in all conditions reported a high intensity of engagement, which in turn may be because the exhibition's topic of animal husbandry and animal welfare is currently highly debated. We can therefore only speculate that there may be benefits of haptic exploration on visit behaviour in a science museum for larger exhibitions and different topics. This should be investigated in subsequent research.

Cognitive outcomes

Schwan and colleagues (2016) established that objects are better remembered than object photos. Our free recall results build upon these findings: The participants in the photo condition remembered significantly less information than the participants in the other two conditions. Furthermore, the participants in the haptic condition remembered more objects and accompanying text topics than the participants in the vision condition. This suggests that the participants who had a haptic experience were able to build the strongest memory trace of the exhibited objects. The additional benefit of object handling has practical implications for the exhibition design: Providing exhibits that can be handled by the visitors can lead to a more pronounced information processing. As most museum's missions and exhibition's aims are to educate, curators (and exhibit designers) should indeed consider object handling as a means to increase visitors' recollection of the objects on display.

That being said, the results of the knowledge acquisition test were less clear. While the ANOVA showed significant differences between the experimental groups, all subsequent pairwise comparisons did not reach significance. There are several reasons why such a pattern of results can occur. Most likely in our case, it is a lack of statistical power. The Tukey post-hoc test is a conservative test with low power. If the post-hoc tests are underpowered, they are less likely to detect significant differences. In addition, the global ANOVA is relatively close to the significance level, which can also lead to the fact that the pairwise comparisons do not become significant.

Motivational-affective outcomes

One key characteristic of the museum learning experience is that it appears in a free-choice science learning setting (Falk et al., 2007). Interestingly, despite the small size of the exhibition, we did find differences in perceived autonomy in our study. Visitors who were allowed to touch the objects perceived more autonomy than visitors who only saw the objects or photos of them. This suggests that the opportunity to touch the objects evokes an experience of self-determination that gives visitors the impression that they can more freely explore the exhibition. This impression matches the experience of autonomy, which represents one of the three basic psychological needs according to the self-determination theory (Ryan & Deci, 2017) and interest theory (Lewalter, 2020; Renninger & Hidi, 2016) and which can be measured by perceived freedom of choice (Wilde et al., 2009). Thus, one can assume that haptic exploration supports one fundamental prerequisite for intrinsic motivation. This has practical implications for the exhibition design: If the free-choice character of the exhibition can be supported by haptic exploration, curators and exhibition designers should provide more hands-on opportunities to motivate museum visitors to engage more deeply with the exhibition content during their visit.

In contrast, the results concerning situational interest as well as positive and negative affect are less clear. We would have expected that the presence of the objects and, in particular, the haptic exploration of these objects would stimulate the curiosity and interest of the visitors as well as their affect. The situational interest should thus be heightened in comparison to the photo condition. However, we found that participants in the photo condition reported a higher situational interest than the participants in the touch condition. It is possible that this unexpected pattern of results can be explained by the topic of the exhibition and the objects on display. The topic of the exhibition is very serious, and the exhibited objects are used for agricultural methods that can be painful for the animals. One could speculate that touching these objects could be perceived as a deterrent and that the situational interest is therefore reduced. But it must be noted that the situational interest reported by the participants in the touch condition is still at a relatively high level. Nevertheless, further research is needed to explain this pattern of results. Particularly relevant would be whether one would find similar or different results when choosing a different exhibition theme.

Likewise, the results of our study regarding the positive and negative affect are difficult to interpret. Considering that handling an object can evoke a range of emotions, positive and negative (Romanek & Lynch, 2008), and considering the results of other studies (Etzi et al., 2016; Oum et al., 2011; Peck & Wiggins, 2006; Skolnick, 2013), we would have expected that the presence of the objects and, in particular, touching these objects would intensify either negative affect due to the nature of the objects (e.g. castration forceps), or positive affect due to the opportunity to touch the objects, or both. In contrast, we found that the participants in the photo condition reported a higher negative and positive affect than the participants in the other two conditions. Further research is needed to explain these results.

Visitor satisfaction

Finally, we wanted to find out if visitors would mention object handling when asked (in an open question format) what they liked best about the exhibition. Wilson et al. (2017) found that touchable 3D printed replicas serve as motivators for visiting museums and that visitors expect object handling to enhance their enjoyment of museum exhibits. In our study, 'haptics/interaction' was the second most frequently mentioned category by visitors in the touch condition, after the more general 'objects' category. This indicates that the participants indeed appreciated object handling as a way of interacting with the exhibition content. Also, while this can only be considered anecdotal evidence, we noticed that the interaction with the objects enhanced the interaction among the participants: While handling the objects, small groups and couples often explained to each other how the objects work and discussed the consequences and suffering involved in using them. This is in line with the suggestion by Christidou and Pierroux (2019) that touch can serve as "communicative signs, mediating interactions with friends and family" (p. 4).

Limitations

There are several limitations of the present study that require further research. Firstly, the mock-up exhibition that the participants in our study could visit was rather small. It would be interesting to know whether the present findings can be replicated in an exhibition that contains a larger number of objects and more information.

Secondly, as visit behaviour was measured by self-report scales, we cannot be entirely certain to which extent the participants explored the objects. However, making video recordings of our participants would have reduced the ecological validity of our study. The goal of our study was to investigate the effect of the haptic exploration in a setting that is as close as possible to the actual museum experience. In future studies, video protocols could supplement the participants' reports of their behaviour to determine in more detail if and how the visual and/or haptic exploration of the objects took place. Thinking of the exploratory procedures identified by Lederman and Klatzky (1987, 2009), such as pressure to obtain information about the object's hardness, it would be very interesting to analyse how exactly haptic exploration is used in a science museum when objects are allowed to be handled.

Thirdly, the topic of the exhibition, animal husbandry, is a rather serious and sensitive topic. Therefore, to generalise the findings of the present study, an investigation of the influence of haptic exploration in the context of a more neutral topic will be necessary.

Finally, it is important to point out that there could be a small bias in the free recall results. As the participants were asked to list 'objects', some of the participants in the photo condition may not have realised that this included the photographs of the objects in the shelving unit. However, the advantage of the touch condition over the vision condition indicates that the haptic exploration is beneficial for retrieval, which was a main focus of this study.

Conclusions

Taken together, we found that the haptic exploration of museum exhibits did have an impact on how well visitors recollect the objects and the topics they represent, on the visitors' perceived autonomy felt during the visit, and how satisfied they were after the visit. However, as we did not find any significant differences in the knowledge acquisition test, it remains unclear if object handling can also lead to a better recollection of the overall exhibition content. We also could not show an advantage of haptic exploration on visit behaviour in terms of the dwell time and engagement nor on situational interest and affect. A special methodological characteristic of our study was that we combined a museum setting with an experimental variation. Thus, we were able to reach not only a controllability of the setting but also a high ecological validity.

Bearing in mind the above-mentioned limitations, the results of the present study do have implications for instructional uses of real objects in different science learning settings in general and in the museum context in particular. If relevant information is transported by the objects themselves, instructors should indeed consider allowing object handling to intensify the learning experience and increase recall. Aside from the fact that handling objects can provide the learner with additional information, such as weight and mechanics/function (Christidou & Pierroux, 2019; Lederman & Klatzky, 1987, 2009), and also potentially increase – as our results suggest – their recollection of the object and its functions, it can also bring learners closer to the original user (Candlin, 2008; Romanek & Lynch, 2008). Romanek and Lynch (2008) suggest that object handling can lead a person to 'have the feeling that the object is a part of themselves, or conversely, that they are a part of the object – an experience of intimacy that will likely be denied when the object is placed behind glass out of reach' (p. 276). When dealing with objects in a science museum, such an experience of intimacy would put the visitor in close(r) contact with the developers and users of the various tools, machines, and other objects on display. In our study, we could not find any direct evidence that object handling influences visit behaviour, but we did find some evidence that touchable objects are appreciated and can increase the visitors' recollection of the exhibition's content. Perhaps the opportunity to handle tools also evoked a better understanding of the animal farmers currently using these exact same objects or, conversely, more sympathy with the animals that the tools are being applied to. Future studies relying on qualitative measures such as interviews would be needed to better understand the overall impact of object handling on the visitor experience.

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References

Adams, K. M. (2015). Back to the future?: Emergent visions for object-based teaching in and beyond the classroom. *Museum Anthropology*, *38*(2), 88–95. https://doi.org/10.1111/muan.12085

Afonso, A. S., & Gilbert, J. K. (2007). Educational value of different types of exhibits in an interactive science and technology center. *Science Education*, *91*(6), 967–987. https://doi.org/10.1002/sce.20220

Agostinho, S., Tindall-Ford, S., Ginns, P., Howard, S. J., Leahy, W., & Paas, F. (2015). Giving learning a helping hand: Finger tracing of temperature graphs on an iPad. *Educational Psychology Review*, *27*(3), 427–443. https://doi.org/10.1007/s10648-015-9315-5

Allen, S. (2004). Designs for learning: Studying science museum exhibits that do more than entertain. *Science Education*, *88*(S1), S17–S33. https://doi.org/10.1002/sce.20016

Bara, F., Gentaz, E., Colé, P., & Sprenger-Charolles, L. (2004). The visuo-haptic and haptic exploration of letters increases the kindergarten-children's understanding of the alphabetic principle. *Cognitive Development*, *19*(3), 433–449. https://doi.org/10.1016/j.cogdev.2004.05.003

Bell, P., Lewenstein, B., Shouse, A. W., & Feder, M. A. (2009). *Learning science in informal environments: People, places, and pursuits*. National Academies Press.

Bitgood, S. (1991). Suggested guidelines for designing interactive exhibits. *Visitor Behaviour*, *6*(4), 4–11.

Breyer, B., & Bluemke, M. (2016). Deutsche version der positive and negative affect schedule PANAS (GESIS Panel). *Zusammenstellung Sozialwissenschaftlicher Items und Skalen*, https://doi.org/10.6102/zis242

Candlin, F. (2008). Mueums, modernity and the class politics of touching objects. In H. J. Chatterjee (Ed.), *Touch in museums: Policy and practice in object handling* (pp. 9–20). Berg.

Chatterjee, H. J. (2008). Introduction. In H. J. Chatterjee (Ed.), *Touch in museums: Policy and practice in object handling* (pp. 1–5). Berg.
Chatterjee, H. J., Hannan, L., & Thomson, L. (2015). An introduction to object-based learning and multisensory engagement. In H. J. Chatterjee & L. Hannan (Eds.), *Engaging the senses: Object-based learning in higher education* (pp. 1–18). Routledge.
Christidou, D., & Pierroux, P. (2019). Art, touch and meaning making: An analysis of multisensory interpretation in the museum. *Museum Management and Curatorship*, *34*(1), 96–115. https://doi.org/10.1080/09647775.2018.1516561
Classen, C. (2005). Touch in the museum. In C. Classen (Ed.), *The book of touch* (pp. 275–286). Berg.
Classen, C. (2017). Introduction. In C. Classen (Ed.), *The museum of the senses experiencing art and collections* (pp. 1–7). Bloomsbury Academic.
Di Franco, P. D. G., Camporesi, C., Galeazzi, F., & Kallmann, M. (2015). 3D printing and immersive visualization for improved perception of ancient artifacts. *Presence: Teleoperators and Virtual Environments*, *24*(3), 243–264. https://doi.org/10.1162/PRES_a_00229
Dohn, N. B. (2011). Situational interest of high school students who visit an aquarium. *Science Education*, *95*(2), 337–357. https://doi.org/10.1002/sce.20425
Etzi, R., Spence, C., Zampini, M., & Gallace, A. (2016). When sandpaper is 'kiki'and satin is 'bouba': An exploration of the associations between words, emotional states, and the tactile attributes of everyday materials. *Multisensory Research*, *29*(1–3), 133–155. https://doi.org/10.1163/22134808-00002497
Falk, J. H., & Dierking, L. D. (2013). *The museum experience revisited*. Left Coast Press.
Falk, J. H., Storksdieck, M., & Dierking, L. D. (2007). Investigating public science interest and understanding: Evidence for the importance of free-choice learning. *Public Understanding of Science*, *16*(4), 455–469. https://doi.org/10.1177/0963662506064240
Gallace, A., & Spence, C. (2008). A memory for touch: The cognitive psychology of tactile memory. In H. J. Chatterjee (Ed.), *Touch in museums: Policy and practice in object handling* (pp. 163–186). Berg.
Gallace, A., & Spence, C. (2009). The cognitive and neural correlates of tactile memory. *Psychological Bulletin*, *135*(3), 380–406. https://doi.org/10.1037/a0015325
Gibson, J. J. (1962). Observations on active touch. *Psychological Review*, *69*(6), 477–491. https://doi.org/10.1037/h0046962
Ginns, P., Hu, F. T., Byrne, E., & Bobis, J. (2016). Learning by tracing worked examples. *Applied Cognitive Psychology*, *30*(2), 160–169. https://doi.org/10.1002/acp.3171
Hannan, L., Chatterjee, H. J., & Duhs, R. (2013). Object based learning: A powerful pedagogy for higher education. In A. Boddington, J. Boys, & C. Speight (Eds.), *Museums and higher education working together: Challenges and opportunities* (pp. 159–168). Ashgate Publishing.
Howes, D. (2014). Introduction to sensory museology. *The Senses and Society*, *9*(3), 259–267. https://doi.org/10.2752/174589314X14023847039917
Hutmacher, F. (2019). Why is there so much more research on vision than on any other sensory modality? *Frontiers in Psychology*, *10*, 1–12. https://doi.org/10.3389/fpsyg.2019.02246
Jones, M. G., & Magana, A. J. (2015). Haptic technologies to support learning. In M. Spector (Ed.), *The SAGE encyclopedia of educational technology* (pp. 331–333). SAGE Reference.
Knogler, M., Harackiewicz, J. M., Gegenfurtner, A., & Lewalter, D. (2015). How situational is situational interest? Investigating the longitudinal structure of situational interest. *Contemporary Educational Psychology*, *43*, 39–50. https://doi.org/10.1016/j.cedpsych.2015.08.004
Kolb, D. A. (1984). *Experiential learning: Experience as the source of learning and development*. Prentice Hall.
Koran, J. J., Morrison, L., Lehman, J. R., Koran, M. L., & Gandara, L. (1984). Attention and curiosity in museums. *Journal of Research in Science Teaching*, *21*(4), 357–363. https://doi.org/10.1002/tea.3660210403
Krapp, A. (2002). Structural and dynamic aspects of interest development. Theoretical consid-erations from an ontogenetic perspective. *Learning and Instruction*, *12*(4), 383–409. https://doi.org/10.1016/S0959-4752(01)00011-1

Lederman, S. J., & Klatzky, R. L. (1987). Hand movements: A window into haptic object recognition. *Cognitive Psychology*, *19*(3), 342–368. https://doi.org/10.1016/0010-0285(87)90008-9
Lederman, S. J., & Klatzky, R. L. (2009). Haptic perception: A tutorial. *Attention, Perception, & Psychophysics*, *71*(7), 1439–1459. https://doi.org/10.3758/APP.71.7.1439
Lewalter, D. (2020). Schülerlaborbesuche aus motivationaler Sicht unter besonderer Berücksichtigung des Interesses. In K. Sommer, J. Wirth, & M. Vanderbeke (Hrsg.), *Handbuch Forschen im Schülerlabor – Theoretische Grundlagen, empirische Forschungsmethoden und aktuelle Anwendungsgebiete* (pp. 63–70). Waxmann-Verlag.
Loomis, J. M., & Lederman, S. J. (1986). Tactual perception. *Handbook of Perception and Human Performance*, *2*, 1–41. https://doi.org/10.1167/9.8.1126
Mayer, R. E. (2014). Cognitive theory of multimedia mearning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 43–71). Cambridge University Press.
Minogue, J., & Jones, M. G. (2006). Haptics in education: Exploring an untapped sensory modality. *Review of Educational Research*, *76*(3), 317–348. https://doi.org/10.3102/00346543076003317
Moreno, R., & Mayer, R. (2007). Interactive multimodal learning environments. *Educational Psychology Review*, *19*(3), 309–326. https://doi.org/10.1007/s10648-007-9047-2
Novak, M., & Schwan, S. (2020). Does touching real objects affect learning? *Educational Psychology Review*. https://doi.org/10.1007/s10648-020-09551-z
Ogawa, R. T., Loomis, M., & Crain, R. (2009). Institutional history of an interactive science center: The founding and development of the exploratorium. *Science Education*, *93*(2), 269–292. https://doi.org/10.1002/sce.20299
Oum, R. E., Lieberman, D., & Aylward, A. (2011). A feel for disgust: Tactile cues to pathogen presence. *Cognition and Emotion*, *25*(4), 717–725. https://doi.org/10.1080/02699931.2010.496997
Paas, F., & Sweller, J. (2014). Implications of cognitive load theory for multimedia learning. In R. E. Mayer (Ed.), *The Cambridge Handbook of multimedia learning* (pp. 27–42). Cambridge University Press.
Peck, J., & Wiggins, J. (2006). It just feels good: Customers' affective response to touch and its influence on persuasion. *Journal of Marketing*, *70*(4), 56–69. https://doi.org/10.1509/jmkg.70.4.056
Renninger, K. A., & Hidi, S. E. (2016). *The power of interest for motivation and engagement*. Routledge.
Romanek, D., & Lynch, B. (2008). Touch and value of object handling: Final conclusions for a new sensory museology. In H. J. Chatterjee (Ed.), *Touch in museums: Policy and practice in object handling* (pp. 275–286). Berg.
Rowe, S. (2002). The role of objects in active, distributed meaning-making. In S. G. Paris (Ed.), *Perspectives on object-centered learning in museums* (pp. 19–35). Routledge.
Ryan, R. M., & Deci, E. L. (2017). Psychological needs. In R. M. Ryan & E. L. Deci (Eds.), *Self-determination theory: Basic psychological needs in motivation, development, and wellness* (pp. 80–101). Guilford.
Schnotz, W. (2014). An integrated model of text and picture comprehension. In R. E. Mayer (Ed.), *The Cambridge Handbook of multimedia learning* (pp. 72–103). Cambridge University Press.
Schwan, S., Bauer, D., Kampschulte, L., & Hampp, C. (2016). Representation equals presentation? *Journal of Media Psychology*, *29*(4), 176–187. https://doi.org/10.1027/1864-1105/a000166
Schwan, S., Dutz, S., & Dreger, F. (2018). Multimedia in the wild: Testing the validity of multimedia learning principles in an art exhibition. *Learning and Instruction*, *55*, 148–157. https://doi.org/10.1016/j.learninstruc.2017.10.004
Sharp, A., Thomson, L., Chatterjee, J., & Hannan, L. (2015). The value of object-based learning within and between higher education disciplines. In H. J. Chatterjee & L. Hannan (Eds.), *Engaging the senses: Object-based learning in higher education* (pp. 97–116). Routledge.
Skolnick, A. J. (2013). Gender differences when touching something gross: Unpleasant? No. Disgusting? Yes!. *The Journal of General Psychology*, *140*(2), 144–157. https://doi.org/10.1080/00221309.2013.781989
Skydsgaard, M. A., Møller Andersen, H., & King, H. (2016). Designing museum exhibits that facilitate visitor reflection and discussion. *Museum Management and Curatorship*, *31*(1), 48–68. https://doi.org/10.1080/09647775.2015.1117237

Smith, D. P. (2016). Bringing experiential learning into the lecture theatre using 3D printed objects [version 1; peer review: 2 approved with reservations]. *F1000Research*, *5*(61), 1–8. https://doi.org/10.12688/f1000research.7632.1
Smith, L., & Gasser, M. (2005). The development of embodied cognition: Six lessons from babies. *Artificial Life*, *11*(1/2), 13–29. https://doi.org/10.1162/1064546053278973
Snow, J. C., Skiba, R. M., Coleman, T. L., & Berryhill, M. E. (2014). Real-world objects are more memorable than photographs of objects. *Frontiers in Human Neuroscience*, *8*, 1–11. https://doi.org/10.3389/fnhum.2014.00837
Spence, C., & Gallace, A. (2008). Making sense of touch. In H. J. Chatterjee (Ed.), *Touch in museums: Policy and practice in object handling* (pp. 21–40). Berg.
Stull, A. T., Gainer, M. J., & Hegarty, M. (2018). Learning by enacting: The role of embodiment in chemistry education. *Learning and Instruction*, *55*, 80–92. https://doi.org/10.1016/j.learninstruc.2017.09.008
Tang, M., Ginns, P., & Jacobson, M. J. (2019). Tracing enhances recall and transfer of knowledge of the water cycle. *Educational Psychology Review*, *31*(2), 439–455. https://doi.org/10.1007/s10648-019-09466-4
Watson, D., Clark, L. A. L. A., & Tellegen, A. (1988). Development and validation of brief measures of positive and negative affect: The PANAS scales. *Journal of Personality and Social Psychology*, *54*(6), 1063–1070. https://doi.org/10.1037/0022-3514.54.6.1063
Wilde, M., Baetz, K., Kovaleva, A., & Urhahne, D. (2009). Überprüfung einer Kurzskala intrinsischer motivation (KIM) [Testing a short scale of intrinsic motivation]. *Zeitschrift für Didaktik der Natuwissenschaften*, *15*, 31–45.
Wilson, P. F., Stott, J., Warnett, J. M., Attridge, A., Smith, M. P., & Williams, M. A. (2017). Evaluation of touchable 3D-printed replicas in museums. *Curator: The Museum Journal*, *60*(4), 445–465. https://doi.org/10.1111/cura.12244