Using contextual-cueing to examine context learning within and across the sense of touch and vision

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General Introduction

Undoubtedly, the environment we dwell on is overstimulated with all forms of sensory input. Be it in the constant buzz of the city, or in a scenic setting, our sensory organs certainly will be overloaded. As an illustration, a beam of light bouncing off numerous objects will hit our retinas, our ears will engulf in a jumble of sound waves coming from unknown sources, and colourful aromas will gently invade our noses, while we experience direct contact with the weather as it touches our skin. As crowded as it appears to be, the various components of a scene do not occur in a random fashion. Rather the opposite, objects and events tend to occur in an orderly and structured manner, giving rise to environmental statistical regularities that form 'contexts'. As an instance, imagine a walk in the main park of the city. However, not only with your mind's eye; recall that representations of the environment are not exclusively visual, but fundamentally enriched by multisensorial input. Thereupon, imagine walking through the park with your 'mind's body' and all its senses'. Subsequently, walking on the grass feels soft, the blended scents from the mosaic of flowers becomes ever vivid, getting the 'sprinkly' sensation felt at the vicinities around the fountain, hearing the joyful waves departing from a nearby playground.

All this information works in great harmony, thus building a rich and reliable representation that not only this park, but several parks in the world can have. This type of environmental learning is a topic that has for some time awakened the interest of a large number of researchers that investigate how spatial regularities are processed, stored and retrieved. Consequently, the uncanny ability humans have to acquire regularities from the environment has been extensively investigated by a series of studies and methods that demonstrated it to be an efficient and economic cognitive ability, capable of facilitating future experiences even weeks after the first encounters. Also referred to as statistical learning in general and context learning in particular, this effect has been reliably shown to take place in the visual, auditory and tactile sensory modalities, proving humans to be all around learners (i.e., Baker, Olson, & Behrmann, 2004; Conway & Christiansen, 2005, 2005; Saffran, Johnson, Aslin, & Newport, 1999). Recall the park illustration, as one can build environmental representations grounded on inputs from multiple senses. It is worth noting however, that the earlier studies investigating context effects in the visual domain have mostly employed natural scenes (i.e., Biederman, 1972; Biederman, Mezzanotte, & Rabinowitz, 1982; Palmer, 1975; Wolfe, 1994). Although revealing, these methods fell short in replicating the basic principles of environment context without the additive effects of confounds not properly addressed, such as individual effects concerning familiarity with the stimuli used.

Nonetheless**,** Chun and Jang (1998) introduced a new paradigm which proved to be a powerful tool to scrutinize the processes involved in environmental statistical learning, they called it the contextual-cueing task. The success of the paradigm is reflected by its wide acceptance and application in a broad range of variations, although it has been almost exclusively applied to the visual domain. To date these investigations have boosted to great heights our knowledge about how humans learn, store and retrieve spatial information implicitly learned. Some of these studies will be discussed in the sections below.

Even though the contextual-cueing paradigm is a well-established one, it is surprising that less than a handful of studies have adapted its principles to test for the capacity of this kind of context learning in different sensory modalities. Regarding the tactile modality, to date only very few studies have investigated the effects of context memory in a tactile task (e.g., Assumpção, Shi, Zang, Müller, & Geyer, 2015; Nabeta, Ono, & Kawahara, 2003). This is surprising because the sense of touch is very important for human-environment interaction.

To this end, a brief review on the main findings and facts concerning visual context learning, tactile processing, and some of the gaps present in the literature concerning the latter, will be addressed in the following chapters. More specifically, this thesis will focus on the investigation of context-based facilitation in tactile search, introducing a tactile version of the contextual-cueing paradigm. Subsequently, this thesis will address how tactile learning is coded in space, and whether touch and vision share memory representations of spatial context.

Chapter I: Statistical learning in vision

Basic phenomenon

Most of the very basic yet fundamental abilities that humans have, build itself up over time, throughout a minimum number of repetitions, and however striking, without intention to learn and/or without awareness. This is true for a broad range of cognitive abilities, including but not limited to language, motor skills, perception, and social behaviours. Much learning is possible because we appear to be highly sensitive, thus adaptable to the recurrent regularities present in our environment. For easy reference, in this thesis we will refer to this phenomenon as statistical learning (SL). Please note that there is currently a debate as to whether SL and implicit learning (IL) should be encompassed under one umbrella term due to its many overlapping characteristics. Nevertheless, this debate is beyond the scope of the current thesis (for a review see Perruchet & Pacton, 2006). Therefore, any mention to either term will merely refer to the ability of learning regularities without being necessarily aware of either or both the process of learning and the learned episodes.

Not surprisingly, the broad meaning of the term reflects the ubiquitous nature of the phenomenon shown to manifest in various strands of work. Examples range from the recognition of statistical regularities (e.g., Fiser & Aslin, 2001; Reber, 1967), over the effects of attention on SL, both in terms of selectivity and processing resources deployed (see Annac et al., 2013; Nissen & Bullemer, 1987). This type of learning has been shown to initiate early in life at infancy (e.g., Kirkham, Slemmer, & Johnson, 2002; Saffran, Aslin, & Newport, 1996), extending to later stages of life in elderly adults (e.g., Campbell, Healey, Lee, Zimerman, & Hasher, 2012; Schapiro, Gregory, Landau, McCloskey, & Turk-Browne, 2014). Additionally, the pervasiveness of SL allows such a process to be observed across a multitude of modalities and stimuli such as syllables (i.e.,Saffran et al., 1996), non-linguistic sounds (i.e., Gebhart, Newport, & Aslin, 2009), tactile stimuli (i.e., Conway & Christiansen, 2005) shapes (Fiser & Aslin, 2001), scenes (i.e., Brady, Konkle, Alvarez, & Oliva, 2008) and spatial locations (Mayr, 1996).

Contextual influence on visual perception

Dwelling in a day-to-day environment would be extremely strenuous should an observer process anew every single object and their relationship to one another every time one experienced a given scene. Take the park stroll aforementioned as an example; it is not surprising to see benches, trees and birds along the way. In addition, one may hear kids screaming and laughing in the background thus easily inferring the existence of a playground in the premises. On the contrary, the mere sight of an unexpected object such as a battle tank would nevertheless "pop out", since the object is out of context, thus shocking the observer to say the least. The sheer amount of information the environment holds requires high levels of dedicated attention at any given time, especially considering that in a rich scene not all, but rather very few items competing for awareness are of immediate relevance (i.e., the green light the pedestrian waits to cross the street), a problem referred to as information overload (Broadbent, 1958). Consequently, understanding the process (es) underlying the selection of relevant information out of complex scenes is of critical importance.

At first instance, the way in which attention is dedicated to an object emerges rather instinctively, by a unique feature that highlights the presence of the object. A number of visual search studies in which a target needs to be found amongst distractors has shown that features such as colour, size, orientation or abrupt transient onsets efficiently capture attention. These visual attributes have such a powerful effect on visual search performance that it is independent on the number of items in the display, a phenomenon referred to as “parallel search” (Chun & Wolfe, 2005; Wolfe, 1994; Wolfe, 1998; Yantis, 1998, 1998). Unquestionably, these studies have shed light on fundamental processes of attentional allocation in visual search; however these types of bottom-up visual cues either seldom occur (i.e., out in the sea, or a field), or they are rather too excessive to serve any reliable use (i.e., walking down a busy street). Conversely, a more appropriate alternative comprises “context frames” (Bar, 2004; Bar & Ullman, 1996; Barsalou, 1992; Palmer, 1975). The term departs from the fact that in reality, objects and events hardly ever occur in isolation, but rather co-occur in scenarios that involve other objects that belong to the same context. Context on its own does not exclude itself from being a source of information overload; nonetheless it helps determine what objects of a scene should be looked at, and the ones that should be ignored.

The studies on the influence of contextual frames extend across a variety of methods, and provide fundamental knowledge as to the works of context on object and scene recognition, eye movement, and attention. A classic example of the influence of context on object recognition comes from the work of Palmer (1975). In his work, observers identified an everyday object (i.e., a loaf of bread) being presented either in a congruent (i.e., kitchen) or incongruent scene (i.e., front lawn). It was found that observers accuracy in identifying a target object was higher in the context-congruent compared to context–incongruent conditions, thus supporting the idea that context enhances object recognition. Likewise, the location (rather than identity) of an object in a scene also plays an important role. For instance, a sofa floating in the sky is not recognised as efficiently as when it is presented in its expected location; on the floor of a living room (Biederman, Mezzanotte, & Rabinowitz, 1982). Similar effects were observed when salient items were presented on a natural scene. As an instance, recognition of a clergyman was more efficient when presented with a church context, but hindered when presented in a football field. Remarkably, background recognition is also facilitated when presented with congruent objects in it (Davenport & Potter, 2004). Early evidence from eye movement studies shows that context guides attention to the most appropriate locations. For example, in a scene with people, the pattern of fixations was highly selective in a sense that eye movements did not stroll in a random fashion across the scene. Instead, fixations were directed most of the time to the faces of the people in the scene (Yarbus, 1967). Similarly, fixations are often directed to regions that are more informative or that offer more predictive value, rather than the less informative part of the scene (Loftus & Mackworth, 1978; Mackworth & Morandi, 1967). Moreover, localization of a specific target embedded in a scene-congruent context requires fewer fixations as compared to when it is placed in an scene-incongruent context (Henderson & Hollingworth, 1999).

There has been a variety of accounts trying to explain the way in which context influences object perception before behavioural responses are executed. These accounts commonly assume that the selective processing of individual objects is accompanied by non-selective pathways, the latter being equivalent to context processing (e.g., Wolfe, Vo, Evans, & Greene, 2011). According to these models, context frames are activated by display summary statistics such as the color distribution or the spatial layout of the items. This gist-like representation forms the context that determines the regions of the scene with high and low saliency (Koch & Ullman, 1985). Thereafter, attention and eye movement are directed from highest to lowest salient regions of the scene, enabling observers to act upon objects or events in these regions more efficiently. Under this view, context effects result from (gist-) representations that are automatically encoded during initial scene processing and specify a range of possible objects that can occur in a scenario, and how they are positioned relative to each other (Biederman et al., 1982). Such representations can guide visual processes in a scene within a few hundred milliseconds of scene presentation (Potter, 1975). However, context effects also involve a top-down component. For instance, Bar (2007, 2009) argues that the successful interaction between the observer and environment is not only based on incoming perceptual information, but rather on the comparison between perceptual input and memory representations, thus resulting in testable predications (i.e., 'are these my keys?'). Therefore, the successful prediction of an event depends on the reliability between bottom-up sensory input and representations stored in long-term memory. According to Bar (2003, 2004), low spatial frequency information from objects suffices for the visual system to trigger predictive processes. Thereafter, this information is compared with an averaged memory representations obtained from previous similar situations. The averaged representation of objects limits the number of likely identities for the attended object and suffices for satisfactory object matching at the basic level for the day-to-day recognition, given that objects in the same basic-level categories are often similar; for example, dogs are similar to each other as compared to cats.

In general, the studies concerning context effects on object recognition and attention guidance have been very informative, and offered considerable ecological validity given that the manipulation of contexts comprised real-world scenes and objects. Naturally, in order to perform these tasks observers must beforehand have rich or at least some background knowledge in addition to considerable visual experience. Because these variables are difficult to control and can interfere with visual processing, the findings available still generate debates. For example, background knowledge may vary across observers depending on one's own previous experience. Moreover, the research field lacks a sensible method to quantify the semantics of a scene and with it the strength of context knowledge.

Finally, yet importantly, natural scene studies do not offer an insight as to how contextual knowledge is learned in the first place. The latter is especially important because contextual knowledge should result from experience, only then interfering with visual processing on a top-down fashion. On this note, the investigation of contextual influences on visual perception would benefit more from a paradigm that addressed these shortcomings in a way that any contextual influence observed is nothing less than a product of sensitivity to meaningful regularities and covariance of locations, objects and events within a scene.

Contextual-cueing of visual search

Motivation

The previous section of this thesis highlighted some important studies and their findings regarding the benefits expedited from environmental regularities towards spatial/object processing. Restate, because in real world situations objects and events tend to co-exist, these associations form contexts that facilitate visual search and object/context identification. Regularly, these associations occur in certain types of environments that are rather stable over time; such contextual information greatly reduces the number of likely objects in a given scene. For instance, the number of possible items expected in a grocery store far exceeds that of items expected in a kitchen. These environmental regularities offer highly informative sets of contextual associations, which the visual system takes advantage.

Undoubtedly, the great effect of context on visual perception is undisputed, however as mentioned earlier, these findings were garnered from studies that employed natural scenes. Of course, the ecological validity of these studies is not to be denied, but the use of natural scenes prevents the findings from being invulnerable to criticism. A serious issue regarding natural scenes concerns the difficulty in experimental control. Some problems include the difficulty in defining context, positional constraints of objects within a scene, background knowledge, and most importantly, how context itself is learned. The latter is especially important because the development of contextual information should be explained by experience, in a knowledge-based “top-down” manner. With the goal to directly address these drawbacks, Chun and Jang (1998, 1999) developed the contextual-cueing paradigm.

The contextual-cueing paradigm

The contextual-cueing paradigm captured the ecological properties that the usual natural contextual studies failed to address. At first instance, it was important to investigate how context was initially learned. In their first study, Chun and Jang (1998) let their observers perform a visual search task in which they had to discriminate the direction of a ‘T’ shaped item target embedded in a set of 11 ‘L’ shaped distractor items as fast and as accurate as possible. This type of search array is somewhat difficult to process, requiring observers to scan several items in order to find the target, and only then being able to discriminate correctly its identity. The ‘context’ is defined by the spatial arrangement of distractors on the screen. In doing so, two types of displays were presented, old and new displays (sometimes referred to as repeated and non-repeated displays respectively). In the original paradigm, 12 old spatial arrays were created. These arrays consisted of a stable relationship between target and distractor locations that repeated once in every block across the experimental session (Fig. 1). The repeated target-distractors association in the old displays mimicked environmental regularities in a way that context could be used to predict target location (Chun and Jiang, 1998; Chun and Jiang, 1999). This particular design, aimed at bringing out observers’ sensitivity to overall spatial information that would potentially lead to target location. The new displays on the other hand were used as control condition. Similar to old displays, the target location was also constant across blocks, so absolute target location probability was equated between the two types of displays. Nonetheless, distractor locations in the new displays were determined randomly in every trial, thus spatial array could not cue target location. The main hypothesis tested concerned the observers' sensitivity to spatial regularities. That is, sensitivity to contextual information should lead to facilitation of search reaction times in old displays compared to search in non-new baseline displays (see Fig.2).

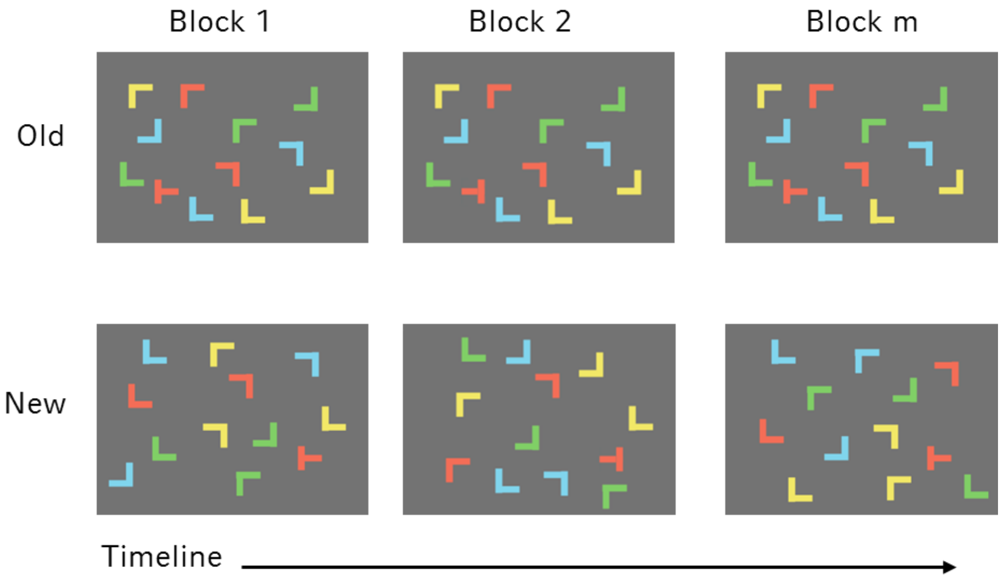

Figure 1. Schematic illustration of old and new displays in Chun and Jiang (1998). In old displays (top panel) both the target and the distractor locations are constant, enabling observers to learn an association between the target and the constant distractor background. In the new condition (bottom panel), only the location of the target is held constant across presentations, while distractor locations vary across trials. Consequently, gains in visual search performance in the old condition can only be attributed to the effects of repeated distractor contexts.

The findings observed in the contextual-cueing task support the authors' hypothesis. Observers discriminated targets embedded in old arrays significantly faster than those embedded in the new ones. This effect is referred to as 'contextual-cueing effect', given that context cues attention to target location. Moreover, the contextual-cueing effect was deemed implicit, as in a yes-no memory task observers discriminated old from new search arrays only at chance levels. Consequently, the authors offered a number of suggestions regarding the mechanisms supporting contextual-cueing. For instance, they proposed that contextual-cueing reflects an interaction between implicit visual memory and spatial attention. That is, search performance increases because of the interaction between memory structures and attention (Desimone, 1996; Desimone & Duncan, 1995). Additionally, the memory underlying old configurations turned out to be highly sensitive to array experience, with some exactitude. Particularly, observers do not benefit from old search arrays in the first encounters, since they lack sufficient memory traces. Nonetheless, providing enough context experience takes place, memory traces sufficiently support the deployment of attention over old search arrays (Logan, 1988, 2002). As an illustration, the cueing effect usually emerges after some 4-6 repetitions of each old display. Concerning the processes in visual search that are affected by contextual-cueing, in their pioneering article Chun and Jiang (1998) surmised that context memory guides spatial attention more efficiently to the target item. According to this view, contextual-cueing aids attentional processes at the level of a topographic representation of the display. On the other hand, contextual-cueing has been shown to facilitate the identification of the target stimulus, for example, by speeding up the perceptual analysis of the target (Töllner, Conci, Rusch, & Hermann, 2013) and / or facilitating response selection (Hout & Goldinger, 2012; Kunar, Flusberg, Horowitz, & Wolfe, 2007).

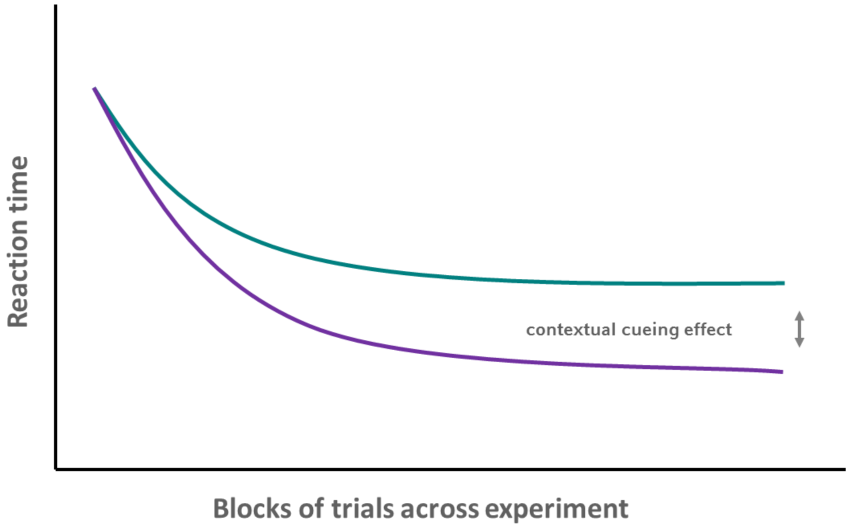

Figure 2. Typical reaction time to target discrimination in the contextual-cueing task. Procedural learning is observed in both old and new configurations. However, as a function of contextual guidance response to target in old displays is faster than response to new displays.

Representations of contextual-cueing

Ever since the contextual-cueing was inaugurated (Chun & Jiang, 1998), the paradigm has been modified to answer an impressive number of questions regarding context learning, and the many factors that interact with it (for a thorough reference guide to contextual-cueing studies see Reference Guide by Zang & Assumpção 2016). Currently, an ongoing debate in the field concerns the possible types of item associations that mediate the contextual-cueing effect. More specifically, some studies have investigated the question whether contextual-cueing effects result from target-distractor or/and distractor-distractor associations. As in respect to the former, Brady and Chun (2007) demonstrated contextual-cueing effects of similar magnitudes both in conditions where only two distractors around the target were repeated compared to when the entire display was repeated. The authors concluded that conserving all distractor locations is not necessary for final context effects, but keeping the association between the target and the neighbouring local distractors were enough to conserve contextual-cueing. The authors formally described the distractor-target association learning with a computational model proposing that contextual-cueing effect arises from associations between the locations of individual distractors and the target, such that the immediate distractors neighbouring target's location have higher weights, thus determining the likely position of the target. As a result the model supported several claims that proposed local over global spatial context predominance on contextual-cueing (i.e., Olson & Chun, 2002; Song, 2005). Supplementary support can be drawn from studies in which the target is relocated at the transition from a learning to a test session (by keeping the distractor configuration nevertheless constant) of the experiment resulted in a reduction or even complete loss of contextual effects (Makovski & Jiang, 2010; A. a Manginelli & Pollmann, 2009; Zellin, Conci, Mühlenen, & Müller, 2013).

An alternative approach however, points out the importance of distractor-distractor association on context learning. Beesley, Vadillo, Pearson, and Shanks (2015) examined the distractor-distractor relationship in a series of experiments by pre-exposing participants to repeated distractors with pseudo-randomly placed targets on each trial, therefore allowing participants to learn configurations in the absence of fixed target location. In a later stage the participants searched displays that were either formed by the pre-exposed configuration (but this time with fixed target locations), or newly generated displays that were only then repeated across the experiment. A comparison of contextual-cueing between pre-exposed and novel repeated configurations showed a pre-exposure effect. In other words, the authors observed faster reaction times to targets in displays exposed prior to the experimental session. This finding led the authors to conclude that contextual-cueing effect does not merely reside in associations between individual distractors and the target, but rather that the recurrent experience of displays leads to multiple associative connections between the distractor items forming the context.

Contextual-cueing and attention

Another very active stream of studies has focused on the question of the role of selective attention on contextual learning. Studies demonstrated that the learning and retrieval of appropriate context are sensitive to information interacting with attentional deployment (Endo & Takeda, 2004; Jiang & Chun, 2001; Jiang & Leung, 2005). An early study by Jiang and Chun (2001) presented displays where a target shared the same color as one half of the distractor set, while the other half was in a different color (i.e., attended and ignored distractor subset respectively), inducing observers to attend only to the subset of distractors sharing target color. The authors observed that contextual facilitation was only expedited when the target shared its color with the attended distractors but not when the ignored items had to be attended in the test session. This finding highlighted the importance of selective attention in the expression of contextual-cueing. Opposing this idea however, with a slightly modified paradigm Jiang and Leung (2005) showed that observers benefited from the ignored subset of repeating distractors as long as it adopted the target color in a test session (Goujon, Didierjean, & Marmèche, 2009). These results showed that attention is particularly important for the retrieval, rather than learning, of contextual cues. Other studies have investigated the interaction of attention, and working memory (WM) tasks with the cueing effect (Manginelli, Langer, Klose, & Pollmann, 2013; Travis, Mattingley, & Dux, 2013). An elegant design by Annac and colleagues (2013) tested whether a secondary spatial WM task would affect context acquisition or/and its expression. To observe whether WM load hinders the gaining of, or recollection from contextual memory, the authors added the secondary task to the contextual-cueing task either during early or late search trials. Additionally, the WM and search tasks were executed either temporally in parallel or in sequence—to dissociate effects of spatial WM load from those of executive load. It was observed that the secondary WM task interfered with the retrieval of learned information only when the tasks were performed in parallel, leading the authors to conclude that spatial WM space links current search trial with configural long-term memory, and when this space is occupied by another task, context retrieval is compromised.

Implicit vs. Explicit memory of learned context

A further line of investigation worth mentioning regards the memory mechanism underlying context learning. To mention a few findings, studies investigating the durability of contextual memory showed that contextual-cueing effects still manifest in a test session conducted even 10 days past the learning session (van Asselen & Castelo-Branco, 2009). Findings along these lines could (at least to some extent) be explained by sleep-based memory consolidation. Geyer, Müller, Assumpção, and Gais (2013) demonstrated that contextual memory was enhanced for participants that took a short nap between learning and test session. Conversely, a control (no-nap) group failed to show improvement in a test session. Finally yet importantly, the level of memory awareness supporting the cueing effect has been a hot topic in the last few years, feeding a rather heated debated in the community. The majority of studies have often supported the view that the cueing effect is supported by implicit mechanisms, such as implicit learning and implicit memory. In other words, context information is coded in an incidental manner, without one’s awareness of what has been learned, as opposed to learning with conscious intention and awareness of the memory recall. Explicit memory of repeated contexts is usually assessed at the end of the search task. This is achieved by introducing a yes-no task in which observers discriminate old and new arrays by pressing corresponding response keys for “yes, I have seen the displays before” and “no, I have not seen it before” (e.g., Chua & Chun, 2003; Chun & Jiang, 1998; Pollmann & Manginelli, 2009). It is common to find that observers perform at chance levels at discriminating old from new displays, thus leading investigators to conclude that contextual-cueing is supported by implicit memory (Assumpção et al., 2015; Chun & Jiang, 1998a; Colagiuri & Livesey, 2016; Conci, Müller, & von Mühlenen, 2013; Geyer et al., 2013). Despite the large number of studies supporting the implicit memory account, this view is not undisputed (Annac et al., 2013; Brockmole & Henderson, 2006a; Conci & Mühlenen, 2009; Geringswald, Herbik, Hoffmann, & Pollmann, 2013; Geyer, Shi, & Müller, 2010; Rosenbaum & Jiang, 2013). Several studies have demonstrated that contextual memory can reach awareness depending on some conditions. For example, paradigms that use search items imbedded in natural scenes formed by rich visual information, found scene memory to be explicit (e.g., Brockmole & Henderson, 2006b, 2006a; Rosenbaum & Jiang, 2013). Additional criticism against ‘unconscious’ context learning departs from the often weak statistical power obtained from memory tests. This idea is supported by the common finding that hit rate (old displays correctly recognised as old) is frequently found to be significantly or marginally significantly higher than false alarm rate (recognising a new display as old). What is more, the way in which the tests are administered (i.e., during, and after search task, objective vs. subject assessment memory tasks) can also reveal contradicting results (Schlagbauer, Müller, Zehetleitner, & Geyer, 2012; Smyth & Shanks, 2008). A recent meta-analysis suggested a number of shortcoming in the traditional methods used to assess awareness of contextual memory; such as the types of memory tests, number of trials and sample sizes, statistical methods and its interpretation (Vadillo, Konstantinidis, & Shanks, 2016). These reasons alone or in combination encourage investigators to base their conclusions in false negatives, given that the findings can sometimes result from insensitive and underpowered tests.

Spatial reference frames of context learning

Imagine a football player warning another team player about a ball pass to the right. Is it the right side relative to the player with the ball (viewpoint-dependent reference frame), or to the receiving team player (external reference frame)? These, and many other ways of coding space are important because they determine where attention is allocated when an observer moves in the environment, and importantly: how search-critical objects are coded in long-term memory. In real life situations, many environments can be viewed and approached from various perspectives, therefore it is important to know where items are in space even though, the layout may look different at first sight. In recent years, a handful of studies employing the contextual-cueing paradigm and a similar task, probability cueing, have investigated the reference frames that support contextual-cueing. Given that context facilitation extends over a period of several days past initial learning (van Asselen & Castelo-Branco, 2009), the paradigm is especially informative as it allows observers to freely change perspective relative to search arrays. For example Chua and Chun (2003) trained observers in the contextual-cueing task with displays being rotated constantly by 0°, 15°, 30°, or 45° relative to the observer (between-subject manipulation). In a subsequent test session displays were always presented in the 0° view angle. As a result contextual facilitation decreased considerably as the angular deviation between training and test displays increased. This suggests that this type of incidental learning is supported by a viewpoint-depended reference frame. Additional work employing the probability cueing task has also shown similar results. In this task, the target appears in a statistically 'rich quadrant' (e.g., 50% probability), whereas the remaining 'sparse' quadrants contain the target in only a small proportion of trials (17% each). In a test session, observers move 90° around the screen (laid flat) and again perform the search task. However, in the test phase the target appears with equal probability in every quadrant. A viewer-centered frame would predict the attentional bias of the learned display quadrant to move with the observer to the next quadrant as the observer moves around the table, whereas an external reference frame of probability cueing would assume that attention is still guided to the original, external coordinates of the rich quadrant. The results supported the former hypothesis. However, there was also evidence for the operation of an external reference frame in probability cueing specifically when observers were explicitly told which quadrant will likely contain the target (Jiang, Swallow, & Sun, 2014) or when observers only tilted their body and/or their heads (Jiang & Swallow, 2013).

Cueing beyond space; object and temporal cueing

"Real" context, in addition to environmental regularities (i.e., a desk on the floor rather than hanging upside down on the ceiling) is also formed by a set of objects that tend to appear together in a given scene. As an illustration, an office is expected to have a desk with a computer atop, perhaps surrounded with papers, pens, pencils and the likes. Consequently, Chun and Jiang (1999) investigated attentional guidance as a function of relationship between objects, namely object-cueing, by means of the contextual-cueing paradigm. The authors paired a target shape with a group of distractors with specific shape. Reaction times were faster to targets detected within the specific pairing, but not when target was presented with a set of distractors with a different shape. This finding later received support from a study that presented repeated configurations that preserved either spatial configuration, items identity or both (Endo & Takeda, 2004). As a result, contextual facilitation was greater when both configural and identity features were repeated, compared to any of the other two conditions alone; thus suggesting an additive effect of context (Hout & Goldinger, 2010). The authors concluded that contextual-cueing is supported by two functionally independent learning mechanisms: space-based and object-based statistical learning.

Insofar, environmental context has referred to structures where spatial configuration and object identities co-vary, which facilitates visual processing such as target location and identification. Nonetheless, these covariations do not only occur in a static world; for instance, cars and bicycles are moving fast in the streets, a ball thrown in a river will stream down along with the current, players of large teams are constantly moving on the field. In 'dynamic event cueing', it is critical to track how one or more objects move over time relative to the observer. Imagine walking in a busy commercial street. As chaotic as it may be, cars, bicycles, and pedestrians follow some environmental norms that help the observer move around, based on previous experiences that lead to predictions to dynamic changes. The process of dynamic context (context formed by multiple moving items) was captured by means of a modified cueing paradigm where search items moved on the screen. For old displays, target and distractors' routes were correlated, thereafter repeated in every block. On the contrary, the trajectories were always random for new displays. As expected, discrimination of target was faster in the predictive routes as compared to the random routes condition. A further variation of the dynamic cueing task was a variant of the multiple object-tracking task. Ogawa, Watanabe, & Yagi, (2009) presented the contextual-cueing task with ten items (five targets and five distractors). Observers tracked the five targets while all items moved around the screen. The authors found that repeated target routes improved tracking performance, especially when distractors trajectories were also repeated. However, repetition of distractor set alone (with random target routes) did not improve tracking, compared to displays with fully random routes (for targets and distractors). In general, these findings show that observes can implicitly learn contexts represented by dynamic changes (multiple object motion routes), thereafter taking advantage of these memories for the tracking of objects in subsequent encounters of the repeated displays.

Neural correlates of contextual memory

The investigation of the neural substrate of associative learning has a long tradition. A classic study worth mentioning, investigated the ability of rats to learn spatial context by having them swimming in a water tank equipped of barely underwater platforms where the rats could rest on once found. The rats efficiently learned the locations of these platforms merely based on spatial references present in the environment, however such spatial learning ability was severely impaired when their hippocampus (HC) were damaged (O'Keefe

& Nadel, 1978). This was one the first compelling evidence for the involvement of the hippocampus in spatial learning that instantly received strong support from others (Cohen & Eichenbaum, 1993; Hirsh, 1974; Johnson, 1994; Kim & Fanselow, 1992; Moscovitch, 1992; Nadel & Moscovitch, 1997; Squire, 1992b; Sutherland & Rudy, 1989).

An early brain imaging study of the cueing effect supported this idea by demonstrating that amnesic patients with damage to the hippocampus and adjacent medial temporal lobe (MTL) areas did not benefit from contextual-cueing, even though they benefited from procedural learning - context independent learning (Chun & Phelps, 1999). These findings, namely HC possible involvement with implicit learning were to some extent ground-breaking, given that HC structures were known to be important for conscious and explicit learning, and memory (Clark & Squire, 1998; Squire, 1992a). Subsequent results demonstrated that HC haemodynamic activity is different between old and new displays (Greene, Gross, Elsinger, & Rao, 2007). These findings nonetheless, were questioned shortly after. Preston and Gabrieli, (2008) observed a positive correlation between contextual-cueing and the activation of the left entorhinal and perirhinal cortex, but not in the HC. Another study found that the contextual-cueing benefit was still present in patients that suffered solely from partial damages to the hippocampal areas, but cueing was impaired in patients with MTL damage (Manns & Squire, 2001).

The contradicting findings regarding the role of the hippocampus have led to an alternative interpretation; that is, that MTL structures (rather than only HC) support context learning. However, based on some of the above-mentioned findings concerning contextual-cueing memory, that the results (and conclusions) from recognition tests are largely dependent on the power of the respective test, it cannot be ruled that MTL (and HC) support explicit rather than implicit learning. This is based on the assumption that observers in the critical studies (Chun & Phelps, 1999; Greene et al., 2007) had explicit knowledge of the repeated arrays, which was nevertheless not detected by the (statistically weak) recognition tests used in these studies. This would give rise to the alternative hypothesis that MTL (HC) is still associated with explicit learning. With an elegant functional magnetic resonance imaging (fMRI) study, Geyer and colleagues (Geyer, Baumgartner, Müller, & Pollmann, 2012) addressed this issue by focusing on the ongoing brain activities in the MTL during processing of repeated displays to which observers had conscious knowledge or not. Individual repeated displays were classified as 'explicit' versus 'implicit' on the basis of a concurrent (and statistically powerful) recognition test. The authors found that 'explicit' displays led to increased activation in the anterior and posterior parahippocampus as well as the HC of the left-brain hemisphere in old compared to new displays. Interestingly, the same brain areas showed relative to the novel baseline reduced activation in implicit displays. Geyer et al. (2012) took these findings to mean that MTL (HC) structures supported the learning of explicit and implicit contextual-cueing displays. However, the learning of explicit and implicit displays is expressed by functionally separable mechanisms (repetition-enhancement versus repetition-suppression, respectively).

Recent studies have shown a broader interaction of brain regions when additional perceptual factors (color) are added to the contextual-cueing task. For instance, by presenting uniquely colored 'reinforcement' displays (in these displays the location of the target and response was held constant across repetitions), Goldfarb and colleagues (Goldfarb, Chun, & Phelps, 2016) demonstrated striatal activations for these displays. Further, HC activation was observed for 'standard' contextual-cueing displays (which appeared in a different color but in which the positions of the distractors were held constant across trials), which were presented intermixed with the reinforcement displays.

Interestingly, responses in these brain regions were highly selective for the type of cueing displays. The authors suggested the existence of multiple memory systems (cf. above) that implicitly guide attention; namely the HC supports attention due to reinforcement learning. A study investigating the neural correlates of reward enhanced contextual-cueing showed that highly rewarded arrays were searched faster even days later, in spite of not being rewarded at test, also resulting in a reward-related fMRI activation, such as an incorporation of memory-guided search and reward processes in retrosplenial cortex.

Chapter II: Tactile memory

What truly defines the existence of something? Perhaps the almost uncontrollable urge to feel with our hands the cold curves of a marble sculpture, or to take a barefoot walk on a cooling summer grass explains at least to some extent a very important link between an idea and reality, namely touch. Whether it is to bring something to 'being', to learn a new sensation, or to create a new memory, the sense of touch is very much active at all times, even though, very often we are not aware of it. The importance of the largest human organ is surely worth a thorough line of investigation; nevertheless, it was not until the early years of the new millennia that tactile investigation went through an exponential growth. Yet in general, tactile research remains rather overlooked if compared to research on visual or auditory sensory modalities.

Part of the reason could owe to the fact that the tactile domain proved to be a rather complex field to investigate. When manipulating an object, several features contribute to its global perception. As an illustration, when handling a teddy bear, in addition to the fluffy sensation exerted by its synthetic fur, one also feels its temperature, weight, shape, size, and the relationship between each part of the object (i.e., head relative to torso and limbs). Following on, the many properties of tactile perception are classified under three main categories; i) microgeometric properties; such as information regarding textures, ii) macrogeometric properties; such as those related to object shape, size, and coarse texture information and iii) cognitive aspects, such as memory for the stimuli presented, e.g., on the body surface (hands). The division of these tactile categories is supported by the existence of specific brain regions involved in the processing of the respective attributes (i.e., Roland, 1987; Roland, O'Sullivan, & Kawashima, 1998). Just as in the teddy bear illustration, most tactile experience involves nearly all the characteristics aforementioned. However, the attempt to replicate natural tactile experiences in the laboratory risks the contamination of findings with a number of extraneous variables. As a result, tactile studies are frequently designed to limit its focus to only a few of these features, often falling under one of two types of tactile studies, specifically, passive and active haptic processing (Gibson, 1962; Loomis & Lederman, 1986).

Regarding precisely research on tactile memory, many studies in this field depart from investigations of other sensory modalities. For instance, an extensive line of research in vision has shown that visual memory consists of different systems, such as short- and long-term memory (i.e., Atkinson & Shiffrin, 1968), explicit and implicit memory (i.e., Brooks & Baddeley, 1976), or semantic and procedural memory (i.e., Anderson, 1986). As in respect to short-term memory, further sub-memory system have been proposed; for example, working memory (e.g., Gilson & Baddeley, 1969; Ricciardi et al., 2006), in addition to other forms of more automatic, sensory memory, including iconic memory (e.g., Sperling, 1960; Cowan, 1984). Perhaps, the diversity of short-term memory per se and the availability of paradigms tapping into this type of memory justify the focus it receives from tactile researchers. As opposed to studies on tactile long-term memory, which to date are rather rare (see below).

Short-term tactile memory

One of the first studies investigating spatial tactile memory had observers reporting the locations where several tactile stimuli were presented (Bliss, Crane, Mansfield, & Townsend, 1966). The stimuli were presented simultaneously to the fingers of both hands. Briefly, the authors found that observers were more successful in reporting stimuli location when providing a partial rather than a full report (all fingers at once). The authors took these findings (partial report > full report) to propose a sensory form of memory for passively experienced stimuli, a system with high capacity but yet short duration, equivalent to iconic memory in vision (Sperling, 1960). Gallace, Tan, Haggard, and Spence (2008) supported this view with the same task but with the stimuli presented across a few different body parts. Again, observers were able to report a greater number of stimuli through partial than through full report. Additionally, it was found that greater numbers of to-be-remembered led to a faster decay of mnemonic representations.

Further evidence of the presence of short-term (iconic) memory in the tactile domain comes from masking tasks. Masking is defined by a deteriorated ability to detect a test stimulus if this stimulus is presented in close temporal succession to a masking stimulus (i.e., Sherrick, 1964). This phenomenon is especially useful for the investigation of tactile memory, as masking effects can be observed when the two stimuli are presented at the very same time, as well as when they are presented successively with time intervals of up to 70 msec between them. However, as the temporal interval between the test and the masking stimulus increases, masking effects decrease (Laskin & Spencer, 1979).These findings led the authors to propose that masking stimulus obstructs a quickly decaying neural representation of the target stimulus.

Following on, short-term tactile memory has been investigated with respect to differences in the sensitivity of different skin sites (i.e., Murray, Ward, & Hockley, 1975). For instance, observers typically display a higher sensitivity to tactile stimulation to their fingers and lips compared to their backs or forearms (e.g., Mancini et al., 2014). In this type of spatial task, participants report whether the location of two skin sites consecutively stimulated were the same. Thus, this task required the representation of the two signals in tactile memory. The authors showed that stimulation to the less sensitive skin sites led participants to report the targeted location as “the same”. Conversely, discrimination of stimulus locations in the more sensitive skin sites were reported more accurately viz. as not being the same (Murray et al., 1975), a result that points to a strong link between tactile processing and storage of tactile information.

Moving on to memory for manipulated objects, namely active haptic memory, the very early studies (i.e., 1960s and 1970s) tended to focus on the differences between visual and tactile memory for the objects' geometric properties such as shape and size, with results often showing only very poor haptic performance compared to other sensory modalities. However, these results have to be interpreted with caution, given that presentation times in the 'early' studies were identical between conditions (modalities). This is a problem because haptic recognition typically requires longer processing times, as object scanning is mostly serial as compared to parallel in the visual modality (e.g., Knecht, Kunesch, & Schnitzler, 1996). Moreover, changes to shape, size, and orientation considerably hamper performance in a recognition task (e.g., Heller, Calcaterra, Tyler, & Burson, 1996; Lederman, Klatzky, Chataway, & Summers, 1990). In contrast, results have been more supportive of a "reliable haptic memory" when the to-be-recognised objects are more ecologically valid; such as familiar objects presented as 3D objects, shapes or even faces (Kilgour & Lederman, 2002; Kiphart, Auday, & Cross, 1988; Klatzky, Lederman, & Metzger, 1985).

Long-term tactile memory

As opposed to the extensive stream of studies focusing on short-term tactile memory, the long lasting forms of tactile memory traces have been rarely investigated; a fact previously highlighted by Gallace and Spence's, (2014) in their thorough review of tactile processing. Yet, the few studies addressing this topic combined crossmodal designs employing the manipulation of 3D familiar and unfamiliar objects (e.g., Giudice, Klatzky, & Loomis, 2009; Klatzky et al., 1985). These studies are prone to criticism, as several alternative explanations apply, specifically concerning the actual type of memory representation subserving haptic memory. Given the shortage of these studies so far, it is vital to call out for more purely tactile studies; we will cover some of the published studies/issues in the sections below. In respect to passive touch, the situation is even more disillusioning, as to our knowledge, not until 2015 was there any record of passive tactile long-term memory studies. This issue is addressed in Study I of this thesis.

Implicit memory

As previously mentioned, memory can fall under two further subsystems; explicit and implicit (Brooks & Baddeley, 1976), also referred to as declarative and non-declarative memory respectively. Simply put, explicit memory requires conscious recollection of learned information, whereas implicit memory refers to stored information that remains hidden from conscious processing. An interesting instance depicts the act of remembering driving lessons as an explicit type of memory, while improved driving skills based on these lessons stand as a form of implicit memory. An early, yet anecdotal example of tactile implicit learning was reported by Claparéde, (1951). Claparede surprised an amnesic patient with a needle prick to his/her hand during a handshake. The next day the patient refrained from shaking Claparede's hand, even though he/she had no conscious memory of the painful episode. The patient's avoidance towards the doctor indicates that she or he implicitly learned the association between doctor and pain. Recent studies however have employed more ethically compliant approaches, yet with clinical population. Maravita (1997) showed that a patient affected by tactile extinction due to cerebral right-hemisphere damage demonstrated considerable implicit learning of (the size of) objects presented to the contra-lesional hand, even though the patient failed to explicitly report the presence of the object. This result was taken to suggest that tactile stimuli are also encoded in the damaged brain, despite not being available for conscious reports (at a more general level, the distinction between conscious and unconscious forms of tactile learning supports the idea of long-term memory being separated into explicit and implicit systems; see, e.g., Squire, 1992a). Furthermore, Ballesteros and Reales (2004) tested a group of Alzheimer's patients as well as a group of elderly and young neurologically healthy observers. In this task, each group had to haptically learn objects for ten seconds in an 'encoding' session (note that objects were not visible in this session). After five minutes, participants had to haptically identify objects (one at a time), including some of the learned objects together with novel objects as fast as possible. Interestingly, the results revealed that the three groups showed a response time advantage for the old objects compared to novel ones. On the contrary, in the explicit recognition task, in which observers had to tell whether an object was old or new (again this task was performed through haptically sensing the to-be-judged objects), Alzheimer's patients performed far worse than the other two groups (performance of the neurological healthy groups were comparable). The authors argued that Alzheimer's patients can show a level of implicit tactile learning that is comparable to that of healthy observers, though they lack explicit knowledge of the previously learned objects.

Concerning implicit tactile learning, only a few studies on healthy participants have been reported (e.g., Conway & Christiansen, 2005; see also Study I of this thesis). Probably the first study reporting implicit tactile learning was conducted by Conway and Christiansen (2005), who tested participants in a variant of the artificial grammar learning – AGL – task (Reber, 1967). Originally, in the AGL task, participants are presented with a sequence of letters that follow specific grammar rules, forming sequences that fall under two categories: "legal" or "illegal" sequences. Of note, participants are not informed about the two grammar rules. After an observation period, participants are asked to classify new letter strings under the two categories aforementioned. In brief, the usual finding is that participants are better than chance in classifying new letter strings under the two categories while at the same time being unable to consciously tell apart legal from illegal sequences. Because participants are unaware of the grammar rules, and unable to verbalize any strategy for string classification, this phenomenon is taken as an evidence for implicit learning. In the tactile version of the AGL, the authors presented participants in a learning phase with vibro-tactile stimuli to the fingers in a consecutive fashion. Legal sequences were formed by a sequential pattern that was repeated in the task, whereas illegal sequences were made up of random sequences across the fingers. In a test session, participants were told to classify the sequence as legal or illegal. Their results were compared to that of a control group that took part only in the test session. In short, sequence classification by the experimental group was significantly superior to that of the control group. Moreover, participants were not able to verbalize the classification method used. The authors took these findings as evidence for implicit tactile learning.

Tactile space representation

Processing space in touch is fundamental for the allocation of attention; this is especially true if an action towards the stimulated skin site is required. Imagine a situation, say, by the swimming pool, where a barefoot person sits with a crossed leg position (i.e., right crossed over left leg). She or he is surprised with a fly landing on her or his right foot. In a normal situation (uncrossed leg), quite instinctively the person would attempt to scare-off the fly by waving her/his hand over the right side where the foot is. However, in this hypothetical situation, the legs are crossed, and before any action, the person needs to consider that, although the fly landed on the right foot, this foot is situated to the left side of the body midline. While in the former situation the scare-the-fly action is expected to be performed with ease, the latter (crossed leg) situation is expected to cause some reaction delay. This is because a conflict between reference frames is taking place when a somatotopic reference frame (i.e., the right foot of my body) deviates from an external reference frames (i.e., the right foot on the left side of the environment). This conflict is a consequence of the action itself: to act upon a sensation to the skin, the anatomical spatial code has to be transformed, or remapped, into an external reference frame, allowing the most apt effector (hand, foot, etc.) to perform the action (e.g., Schicke & Roder, 2006). Importantly, after the remapping, responses could be entirely based on the external code – in which case crossed hands would be less reliable, thus leading to performance disadvantages – and / or the original anatomical frame would still be available and delay processing due to its discrepancy with the remapped, external code (these issues are considered below). Note that the term 'external' is an umbrella term for various references frames that deviate from somatotopic, skin based reference frames. Thus external frame could be bound to parts of the body (i.e., body-related), as well as reference outside the body (Badde & Heed; 2016).

In order to investigate the roles played by different reference frames in touch-based localization in space, studies usually manipulate observers' body posture during a tactile task. A very popular manipulation requires observers to adopt a crossed limb position. Such manipulations prompt the conflict between the skin- and external reference frames (Driver & Spence, 1998; Yamamoto & Kitazawa, 2001). By engaging the limb crossing manipulation, some studies claimed that the two main frames are processed in a serial fashion leading to the aforementioned remapping process (serial account), while more recent accounts propose that the two frames coexist and the external can dominate the anatomical frame, which is dependent on sensory and cognitive factors (integrative account; cf. Badde & Heed, 2016). For example, studies on neuropsychological patients suffering from tactile extinction and hemispatial neglect demonstrated that patients were unable to detect a tactile stimulus on the hand contralateral to their lesion. However, with crossed hands, their inability for detecting the tactile stimulus was now bound to the space rather than the hand contralateral to the lesion, suggesting that these patients coded touch in an external reference frame (Aglioti, Smania, & Peru, 1999; Smania & Aglioti, 1995). The dominance of an external reference frame has also received support from a series of crossmodal studies addressing spatial processing (i.e., Driver & Spence, 1998; Kennett, Spence, & Driver, 2002), temporal processing (e.g., Bruns & Roder, 2010; Spence, Pavani, & Driver, 2004; Spence & Walton, 2005), up to electrophysiological investigations of tactile processing (e.g., Eimer, Cockburn, Smedley, & Driver, 2001). The latter revealed that event related potentials (ERPs), such as the P100 and N140 measured above the somatosensory cortex and indexing the operation of tactile attention (Eimer & Forster, 2003), were reduced or even extinguished in the crossed relative to uncrossed hand condition (Martin Eimer, Forster, & Van Velzen, 2003). Finally yet importantly, the temporal order judgment – TOJ – task is very likely the most used paradigm in the investigation of tactile spatial coding (for a review see Heed & Azañón, 2014). In this task, observers report the temporal order of two very fast consecutive stimuli applied usually to two different skin sites, often one in each hand. The TOJ task is very sensitive to limb crossing, leading to performance impairment when limbs are crossed compared to uncrossed (i.e., Azanon & Soto-Faraco, 2007; Azanon, Stenner, Cardini, & Haggard, 2015; Cadieux, Barnett-Cowan, & Shore, 2010; Schicke & Roder, 2006).

An alternative line of studies has instead supported the prevalence of the anatomical, skin based reference frame. For instance, one of the findings emerges from a tactile version of the Simon task, an effect that reflects a facilitation of response when a stimulus is presented to the same relative location as the response itself. In the tactile version, observers discriminated between high- and low-intensity stimuli that could be presented to the right or left hand. Responses were given via corresponding foot pedals, e.g., high (low) intensity = right (left) foot). Stimulus and response assignments could therefore be congruent or incongruent. The results showed an advantage for congruent responses; say, right foot response was faster to stimulus to the right hand regardless of limb posture (Medina, McCloskey, Coslett, & Rapp, 2014). Further support comes from studies investigating temporal judgment of spatially distinct but consecutive tactile stimulations (Kuroki, Watanabe, Kawakami, Tachi, & Nishida, 2010). In this study, the authors manipulated somatotopic and spatiotopic distance between the two stimuli in an independent fashion. The results showed that judgements were affected by somatotopic, but not by spatiotopic, distance between stimuli (for somatotopic prevalence on a tactile version of inhibition-of-return task see Tassinari & Campara, 1996). Finally yet importantly, a further stream of electrophysiological studies proposes the concurrent existence of somatotopic and external reference frames. A recent study by Schubert et al. (2015) involving an attention task which did not require a motor response towards the target, revealed the concurrent coding of external, and somatotopic tactile spatial information in beta and alpha band activity (for further evidences derived from EEG and magneto encephalography – MEG see Buchholz, Jensen, & Medendorp, 2011; Buchholz et al., 2011; Buchholz, Jensen, & Medendorp, 2013).

Interestingly spatial remapping (in the TOJ task) has been interpreted as a serial process based on the grounds that tactile perception initially follows the organization of the primary sensory cortex (anatomical reference frame), with these representations being subsequently translated into external spatial coordinates (e.g., in an attempt to make a response). The serial view holds the anatomical code as a mere precursor frame that becomes obsolete once tactile representations are remapped onto an alternative, external reference frame. Nonetheless, the recent findings concerning the concurrent use of anatomical and external reference frames gave rise to an alternative view that assumes that tactile events are rather coded in both anatomical and external coordinates, referred to as 'integrative account'. The integrative account suggests that errors following limb crossing in localization tasks emerge when incompatible anatomical and external reference frames are integrated (Schubert et al., 2015). Further support for the integrative account arose from a comparison between models that assimilated assumptions associated either to the serial, or to the integrative account. The results revealed that the integrative model outperformed the serial model in explaining observers' behaviour in a series of tactile tasks (Badde, Heed, & Roder, 2016). It is important to point out, that a number of factors may influence the ways in which the optimal reference frames is defined, such as visual information, task context, and working memory load, just to name a few (for review see Badde & Heed, 2016).

Of note, it is important to highlight that, these studies have employed paradigms that access very short periods of memory, and transient types of attention. That is, at least to date, there has been no record of studies investigating reference frames of long lasting forms of tactile attention or memory traces that lasts longer than a few seconds. Study II will fill this gap, by investigating the reference frames used in the tactile version of the contextual-cueing task. This type of learning is supported by long-term tactile memory.

Neural correlates of tactile memory

Research regarding the neural correlates of tactile memory has been quite fruitful, usually demonstrating that tactile memory is represented in the brain by a series of networks consisting of unimodal as well as amodal/multisensorial processing neural circuits. For example, the topography of tactile learning and memory in adult humans was addressed in an elegant psychophysical experiment by Harris, Harris, and Diamond (2001). In their study, participants compared two successively presented stimuli (i.e., vibration frequencies) separated by variable inter-stimuli intervals ranging from 0.2 to 5 seconds. The second stimulus was presented either to the same or a different finger, including the same finger of the opposite hand, as well as the adjacent or distal finger of the same hand. The results showed that when inter-stimulus interval was shorter than 1 second, observers were more accurate when stimuli were delivered to the same finger, while accuracy dropped down (in the same-finger condition) as the temporal distance between stimulated fingers increased. However, at retention intervals greater than 1 second, performance was comparable across all fingers (e.g., same, homologous, adjacent or distal). The authors took these findings to mean that tactile working memory is supported by somatotopic and spatiotopic representations. More specifically, Harris et al. (2001) suggested that within the first second of stimulus presentation, the memory trace is represented somatotopically, following the organization of the primary somatosensory cortex (S1), where organisation conserves the somatotopic arrangement of skin sites (e.g., Narici et al., 1991; Penfield & Boldrey, 1937). Conversely, and following retention intervals exceeding 1 second, tactile memories are supported by spatiotopic representations (organization does not conserve the topographic arrangement of skin sites). In such case, memories are believed to be stored at the secondary somatosensory system level (S2), where the presence of neurons with bilateral receptive fields has been reported (Iwamura, Iriki, & Tanaka, 1994). The S2 has also been shown to host neurons active during processing of tactile input, with prolonged activation even after stimulation (Hernández, Zainos, & Romo, 2000). The same activity is not observed in S1 (however see Koch & Fuster, 1989; Zhou & Fuster, 1996). In general, these findings suggest the very same area responsible for early tactile processing is also involved in tactile working memory (see next paragraph).

Moreover, brain imaging studies revealed a number of neural networks involved in tactile working memory. As an instance, in an fMRI study by Ricciardi and colleagues (2006), observers compared sequentially presented 2D and 3D matrices in the scanner while their cortical activity correlated with retention and recognition of these matrices was measured (visual and the tactile modalities were compared with an identical experimental design). The results revealed cortical regions that were solely involved in tactile stimulus retention, such as specific posterior areas encompassing the somatosensory cortex. Interestingly, both visual and tactile spatial memories activated frontoparietal networks, recruiting regions such as the posterior parietal cortex, the dorsolateral prefrontal cortex and the anterior cingulate cortex, thus feeding in the idea of a supramodal memory representation in the brain (for single cell recording support see Zhou & Fuster, 1997). Additionally, these findings support the aforementioned idea that the brain areas concerned with stimulus encoding are also involved with stimuli retention in tactile processing (i.e., posterior regions of the brain and the somatosensory cortex).

As in respect to tactile long-term memory neural correlates, the evidence available emerges from tasks involving haptically explored objects. Bonda, Petrides, and Evans, (1996) had participants exploring abstract shapes and subsequently matching them with a set of learned stimuli while regional cerebral blood flow was measured by means of positron emission topography (long-term memory task). This task was compared with a different task in which participants judged the re-appearance of shapes during the scanning (meant to reflect the operation of working memory) and a control task where no memory was necessary. While activation was observed in central opercular regions and the posteroventral areas during both memory tasks, the perirhinal cortex was particularly involved in the task involving tactile long-term memory retention. The authors proposed that long-term representation of tactile experiences are generated, incorporated and stored by a system formed by a ventrally directed parietoinsular pathway, bound to the perirhinal cortex and the posteroventral insula (see also Burton & Sinclair, 2000). Moreover, brain damaged patients suffering from tactile agnosia (inability to recognize an object by touch) were likely to have lesions to the insula as well as to the retroinsular cortex and posterior parietal cortex (i.e., Caselli, 1993; Reed & Caselli, 1994; Reed, Caselli, & Farah, 1996). Despite this evidence supporting the involvement of the insula in tactile long-term memory, a series of studies demonstrated that this region is also involved in stimulus retention across different modalities (e.g., Davies, Graham, Xuereb, Williams, & Hodges, 2004; Manes, Springer, Jorge, & Robinson, 1999; Pietrini et al., 2004), again supporting the view that the network involved in the retention of tactile information is also involved in information storage across different sensory modalities. Additional neural networks have also been found to be involved in tactile and visual representation of objects such as the intraparietal sulcus (Grefkes, Weiss, Zilles, & Fink, 2002) and occipital-temporal cortex of the left hemisphere (Feinberg, Rothi, & Heilman, 1986).

Tactile memory representation

The previous sections in this chapter mentioned a series of tactile studies that revealed the works of fundamental mechanisms as well as neural correlates supporting tactile memory. Nonetheless, it is important to note that research on tactile memory and its representation, especially the early studies are prone to alternative explanations; that is, very often tactile memory representation can be confounded, or at least supported by one or more alternative coding processes (i.e., mental/visual imagery, semantic coding or/and spatial coding). This idea receives support from several studies that demonstrated crossmodal communications in some tasks, as well as compelling amounts of brain imaging data showing activity in areas that are predominantly unimodal (i.e., visual areas), but that are active during processes in different modalities (e.g., tactile processing). For example, efficient haptic common-object recognition might as well be explained by concrete visual representations (e.g., Klatzky et al., 1985; Lederman & Klatzky, 1997), or performance in a serial order judgment of stimuli to the fingers (Gallace et al., 2008; Watkins & Watkins, 1974) could have been coded spatially or visually with reference to some body-related reference frame.

Consequently, a considerable part of 'follow-up' studies shares a common, yet fundamental goal that is to pin down the exact forms of representations underlying tactile memory. As an illustration, to define whether tactile memory of objects was supported by a 'central' memory representation, rather than a tactile representation on its own, Gentaz and Hatwell (1999) asked participants to haptically scan and reproduce a rod's orientation. In between object scan and orientation recall, participants had to perform a secondary task (haptic or semantic). In short, both interpolated tasks equally interfered with haptic memory of the object leading to a deteriorated replication of the rod's initial orientation. The authors concluded that tactile memory is encapsulated in a higher-order form of – multisensory – memory.

An exclusive segment of studies has investigated the influence of mental/visual imagery in tactile memory (for a review see Gallace, 2013). Interestingly, research investigating the phenomenon demonstrated that mental imagery can, to some extent facilitate tactile perception and memory in both sighted and visually impaired population. In one example, both blind and sighted participants were able to accomplish (though the former less accurately) an object comparison task and an imaginary spatial navigation task through haptically explored 2D and 3D matrices, thus suggesting that mental images derived from tactile processing can be used by both sighed and blind groups (Aleman, van Lee, Mantione, Verkoijen, & de Haan, 2001). Somewhat in line, other studies demonstrated that mental imagery abilities decline in cases of acquired blindness, and is likely non-existent in those congenitally blind (e.g, Hollins, 1989).

In general, while the ability to perform mental imagery by both sighted and visually impaired populations has been documented, the true basis of performance in these tasks is still debatable, that is, whether representations are generally visual or spatial (Bértolo, 2005). The aforementioned studies employing manipulations of non-spatial visual and spatial visual materials during tactile memory tasks were very effective in helping to determine the underlying representation of tactile memory. Further research should aim to improve these methods and provide further evidences for this matter, especially in respect to passive touch processes involving long-term memory; a line of investigation virtually ignored by the tactile research community.

Transfer between touch and vision

Much of the investigation concerning tactile processing, has been based on processes known to be functional in sensory modalities such as the visual and auditory ones. Recall the previous sections of this chapter mentioned a few studies that have been replicated in the tactile modalities, such as the serial order judgement, Simon effect, priming effects, and numerosity judgement just to name a few. These studies enabled the comparison of different senses, such as their contribution, and importance to overall perception to a multisensorial level. Following the replication of the various paradigms and effects across multiple modalities, researchers have been trying to understand the extent to which cognitive process across different sensory modalities are supported by common mechanisms. One effective way to investigate the communication between different modalities involves the administration of crossmodal studies. In a typical design, observers learn a certain material, or gain skills on a certain task in a learning session using one modality. In the following minutes, hours or days after the learning session, observers are then tested in a recall session through an alternative modality.

As in respect to transfer of memory between modalities, studies have successfully demonstrated a certain level of abstractness of memory representations between the visual and haptic modality; usually indexed by a transfer of learned information across these senses. Easton, Srinivas, & Greene (1997a) observed such crossmodal facilitation in a crossmodal priming study. The authors asked participants to read a series of words either visually or haptically. In the test session, participants either felt or read three-letter word stems and completed them with the first word longer than three letters that came to their minds. Providing the word stems were scanned in a serial fashion, crossmodal priming transfer was comparable to that of within modality priming. The authors took these findings to suggest the presence of a shared representation for the different sensory modalities. Nonetheless, because priming transfer in this specific study can as well be explained by a mediation of lexical representations, the authors used novel 2D patterns and common 3D objects to exclude this alternative account (Easton, Greene, & Srinivas, 1997b). Briefly, successful crossmodal priming transfers were observed; what is more, the magnitude of transfer was almost comparable between the crossmodal and uni-modal conditions. Consequently, the authors ruled out lexical representations, again suggesting that perceptual representations subserving perceptual implicit learning are not modality-specific.

As in respect to transfer of implicitly learned spatial context across modalities, Nabeta et al. (2003) showed a successful transfer of context facilitation of search performance from vision to haptics. The authors trained participants in a visual contextual-cueing task where search displays could be predictive of the target location in half of the trials (repeated-context), and non-predictive in the remaining trials (non-repeated-context). Even though participants were unaware of context repetitions, target discrimination was significantly faster in repeated contexts. In a transfer session, participants haptically searched the displays that replicated the repeated displays learned in the visual part of the experiment. Remarkably, visual contextual facilitation was transferred to the haptic search. Moreover, contextual regularities were learned implicitly, as participants failed to discriminate repeated and non-repeated contexts in a forced-choice recognition text. The authors took these findings to mean that spatial regularities implicitly learned through visual search is sufficiently abstract to allow the access of haptic processes, thus facilitating the allocation of attention in haptic search.

It is important to mention though, that Nabeta and colleagues (2003) neither tested the capability of the tactile modality to learn repeated search displays (rather than benefitting from transfer) nor did they test for a transfer of learned contextual-cueing displays from the tactile to a visual search task. Future studies could address this issue and answer interesting questions as to whether tactile search can benefit from predictive contexts and if so, whether spatial regularities learned through tactile search would facilitate visual search. Assuming that context learning in modality X facilitates search in the alternative modality Y - and vice versa, one can further investigate the nature of the transfer effects as being symmetric or asymmetric, with the former constituting evidence of a supramodal context memory. However, and given that the contextual-cueing task is spatial in nature, it is also plausible to expect a visual dominance in this task (Welch & Warren, 1980), which could lead to an asymmetric transfer of learned display arrangements from the visual to the tactile task. On the other hand, the detection of the target in tactile search requires scrutiny of temporal processing, if the target is defined by a frequency (i.e., temporal) difference relative to the distractor items. Given that touch dominates vision in temporal processing (for a review see Hidaka, Teramoto, & Sugita, 2015), it is also possible that context learning in this task particularly benefits the detection of the target in a subsequent visual task.

The notion of sensory dominance in crossmodal processing was recently supported by a very elegant study by McGovern, Astle, Clavin, and Newell (2016). In their study, participants took part in one of two tasks; a spatial or temporal discrimination task, with the two tasks being performed either visually or aurally. After a training period, participants showed considerable improvement in their trained tasks/modalities. Subsequently, the authors showed that when participants performed a test session, transfer of perceptual learning was asymmetrical, such that, successful transfer was only observed when a given task was originally trained with the most appropriate modality (i.e., spatial task preformed visually, and temporal task performed aurally). In other words, spatial learning acquired visually transferred to a spatial task when this task was later on performed with auditory stimuli, however when spatial learning was originally acquired under auditory stimulus conditions, training gains did not transfer to the visuospatial task (performed then with visual stimuli). Similarly, learning-related gains from a temporal task initially performed with auditory stimuli were transferred to a visual version of this task. On the contrary, a temporal task performed visually did not transfer its benefit to a subsequent test session, when auditory stimuli were used. The authors took these findings as evidence for crossmodal sensory calibration, which posits that the modality more accurate for a given task will calibrate the non-dominant modality (Gori, Del Viva, Sandini, & Burr, 2008). More specifically, the superior representation in the dominant sense will indirectly benefit the other sense, whereas learning with the non-dominant sense will limit to sensory specific learning effects. Study III of this thesis will investigate the crossmodal transfer of context learning between tactile and visual search.

Chapter III: Cumulative work

Study I: Tactile contextual-cueing

Contextual-cueing: implicit memory of tactile context facilitates tactile search

Summary

An extensive line of visual studies has convincingly demonstrated that humans can effortlessly take advantage of statistical regularities present in the environment, which in turn facilitates search performance once the learned context is re-encountered. The contextual-cueing paradigm (Chun & Jiang, 1998b) stands out as a rather revealing tool regarding the processes underlying spatial learning. As seen in previous chapters, the contextual-cueing paradigm demonstrated that visual search of complex arrangements becomes faster over time because learned target-distractor spatial associations (stored in LTM) come to guide the search, cueing attention to – or predicting – the target location. Interestingly, context leaning is deemed implicit, as observers fail to tell apart repeated from new displays in a forced memory task. While study after study further explored the cueing effect in the visual modality, the scientific community disregarded the participation or even the independent capacity of other sensory modalities for context learning. It is true that humans are visually dominant; however, this does not exclude the possibility that also other sensory modalities play an important role in spatial learning. For example, does the tactile modality display the capability for context learning? The first study of this Thesis focuses on this very important question. Here, we designed an experiment that replicated the most important features of the visual contextual-cueing task. That is, we presented observers with repeated and non-repeated tactile configurations. Each configuration consisted of four stimuli (one target with three distractors), always comprising two stimuli on each hand. All fingers but the thumbs were used as possible item locations. Observers reported either the location (Experiments 1 and 2) or the identity (Experiment 3) of the target by pressing a corresponding foot pedal as fast and as accurately as possible. Similar to visual contextual-cueing, in the three tactile-search experiments observers were faster in detecting the target

in repeated compared to non-repeated configurations. The findings from this study revealed that the tactile modality too, can form its own spatial memory, thus speeding up target detection when the target was embedded in a learned configuration. Moreover, a follow up memory task (administered in Experiment 3) revealed that observers were not better than chance at discriminating repeated and non-repeated configurations, deeming the tactile context learning as implicit. This study was the first to show that the tactile sense alone can form an exclusively tactile spatial representation.

References

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Abstract

In visual search, participants detect and subsequently discriminate targets more rapidly when these are embedded in repeatedly encountered distractor arrangements, an effect termed '*contextual-cueing*' (Chun & Jang, 1998). However, while previous studies explored contextual-cueing exclusively in *visual search*, the present study examined the effect in *tactile search* using a novel tactile search paradigm. Participants were equipped with vibro-tactile stimulators attached to four fingers of each hand. A given search array consisted of four stimuli (two items were presented to each hand), with the target being an odd-one-out feature singleton differing in frequency (Experiment 1 and 2) or waveform (Experiment 3) from the distractor elements. Participants performed a localization (Experiments 1 and 2) or discrimination (Experiment 3) task. Responses were delivered via foot pedals. In all three experiments, reaction times (RTs) were faster when the arrangement of distractor fingers predicted the target finger. Furthermore, participants were unable to explicitly discern repeated from non-repeated tactile configurations (Experiments 2 and 3). This indicates that the tactile modality is able to form configural representations and use these representations to guide tactile search.

Introduction

Humans are experiencing a myriad of events at any given time, presenting an excessive load of information to the brain. However, most events or objects do not occur in isolation, rather, they are embedded in larger, structured environments. Previous work has shown that environmental regularities are permanently retained and facilitate visual perception. For instance, in a seminal study by Palmer (1975; see also Biederman, Mezzanotte, & Rabinowitz, 1982; Biederman, 1972; Chun, 2000; Hollingworth & Henderson, 1998), participants were presented with a scene context (e.g., a kitchen counter) followed by a brief presentation of a target that was either context-appropriate (e.g., a loaf of bread), context-inappropriate but similar in shape to the appropriate object (e.g., a mailbox), or completely context-inappropriate (e.g., a drum). In a subsequent naming task, participants showed higher performance accuracy in the context-appropriate compared to the two context-inappropriate conditions. Palmer (1975) concluded that *visual object recognition* is modulated by scene context.

The beneficial effect of environmental information on *visual selective attention* was further elucidated by Chun and Jang (1998), by means of their contextual-cueing paradigm. In this task, participants have to detect and subsequently discriminate the orientation (left vs. right) of a target ‘T’ embedded in a set of distractor ‘L’s. Unbeknownst to participants, half of the trials contain repeated and the other half non-repeated target-distractor spatial arrangements. In the repeated – *Old* – condition, both the target and the distractors are presented at identical display locations across trials. By contrast, in the non-repeated – *New* – condition, only the targets (but not the distractors) appear at identical locations (by keeping target locations constant in Old and New displays, one can equate target location repetition effects between the two types of display and thus isolate the effect of context on reaction time – RT – performance). Chun and Jiang (1998) found that participants were faster in detecting the target in Old compared to New displays, an effect referred to as '*contextual-cueing'*. Interestingly, when participants were asked to discern repeated from non-repeated displays, explicit recognition was only at the chance level. This dissociation in direct (recognition) and indirect (RT) measures led Chun and Jiang (1998) to surmise that contextual-cueing is supported by an implicit memory system.

In recent years, Chun and Jiang's (1998) basic findings and paradigm have inspired numerous studies. For example, van Asselen and Castelo-Branco (2009) showed that contextual-cueing was still obtained in a test session when the training and test sessions were separated by 10 days. Geyer, Müller, Assumpção, and Gais (2013) found that even a short nap relative to an equivalent period of controlled rest separating the learning and test sessions (on the same day) was sufficient to enhance contextual-cueing. Other investigations have demonstrated that, rather than relying on the entire distractor context, contextual-cueing is supported by memory for individual target-distractor (paired) associations formed particularly in the vicinity of the target (Brady & Chun, 2007; Jiang & Wagner, 2004; Shi, Zang, Jia, Geyer, & Müller, 2013), or amongst those sharing the target's color (Conci, Müller, & von Mühlenen, 2013; Geyer, Shi, & Müller, 2010). Additional work showed that contextual learning (i.e., acquisition of contextual memory) and expression (i.e., retrieval of contextual memory) are separate processes (Chaumon, Schwartz, & Tallon-Baudry, 2009) and that an additional (spatial working memory) task interferes with the retrieval, but not the learning, of contextual memory representations (Annac et al., 2013).

Taken together, the by now extensive body of studies on contextual-cueing in *visual* search has contributed substantially to our understanding of the processes underlying *implicit spatial learning*. Although sensory modalities other than vision have received considerable interest in recent years (e.g., Klatzky, Lippa, Loomis, & Golledge, 2002, 2003; Yamamoto & Shelton, 2009), little is known about the roles of these senses for implicit context learning. Concerning the haptic/tactile sense, although still modest, a growing number of studies have revealed intricate processing capabilities of this modality. For example is has been demonstrated that features like material dimensions and abrupt surface are likely to produce low search function slopes, suggesting a parallel search, whereas orientation and 3-D surface contours are likely to yell somewhat steep slopes, suggesting serial search (Lederman & Klatzky, 1997). More recently a study focusing on manual 3D search task, demonstrated that saliency was an important factor in determining what parts of the hand and what strategies were used to contact the target, suggesting that non-salient conditions was more likely to engage the thumb in a serial strategy, while in the salient target conditions, parallel strategies such as grasping and shuffling of the items in the hand were applied (van Polanen, Bergmann Tiest, & Kappers, 2014). In respect to spatial learning and representations, it has been claimed that the haptic sense can facilitate (the updating of) visual-spatial representations (Shelton & McNamara, 2001), or even that participants are able to form entirely new spatial representations in an explicit learning task on the basis of haptic information alone (Pasqualotto, Finucane, & Newell, 2005). However, whether the tactile sense is capable of forming its own *implicit spatial representation* and to what extent such representations can be used for attentional guidance remains an open question. This is the issue we investigated in the current study.

Hitherto, to our knowledge, there is only one study, by Nabeta, Ono, and Kawahara (2003), that has attempted to investigate haptic contextual-cueing. Nabeta et al. found facilitation of RTs for Old relative to New *haptic* arrangements when the Old (haptic) arrangements were learned in a preceding visual search task (the same arrangements were used in the visual and haptic tasks). However, it was not clear whether this haptic contextual-cueing effect was driven by haptic or visual representations. That is, it could not be ruled out that in the haptic task, participants may have continued to operate an essentially visual strategy (see, e.g., Lederman, Klatzky, Chataway, & Summers, 1990, for the effects of visual imagery on recognition performance in a haptic discrimination task). For example, participants may have registered the haptically sensed stimuli in a visuo-spatial representation maintained in working memory, and it may have been this representation that, when critical (context) stimuli had been sampled and recorded, triggered the matching visual context information stored in long-term memory, thus guiding the haptic search to the (visually represented) target location. Note that participants in Nabeta et al. did not see the haptic displays, so search could ultimately only be based on some actively built-up and maintained spatial working memory representation. In other words, observed haptic contextual-cueing might well have been visually mediated. Furthermore, Nabeta et al. did not address the fundamental question; that is whether contextual regularities can also be acquired in – rather than in one way or another ‘transferred’ to – the haptic modality. The present study was designed to examine this question.

Participants were tested in an exclusively tactile search task, which adopted the original approach (Chun & Jiang, 1998) with half of the trials containing Old and the other half New arrangements. In Experiment 1, we investigated contextual-cueing in tactile search, while in Experiment 2 we assessed participants’ explicit knowledge of repeated tactile arrangements. In Experiment 3, we introduced a discrimination task in order to dissociate contextual-cueing of target selection from contextual-cueing of response selection.

Experiment 1

Method

Participants Nine naïve participants (8 females, 8 right-handed, age range 24 to 41 years) took part in this experiment for either course credit or 8.00 Euro/hour. All participants reported normal tactile perception, and no history of somatosensory disorders. Participants gave informed consent prior to performing the experiment, which was approved by the ethics committee of the Department of Psychology at LMU Munich, in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Apparatus and Stimuli The vibro-tactile stimuli, 100-Hz and 30-Hz vibrations, were generated by 8 solenoid actuators that activated lodged cylinder metal tips when the solenoid coils were magnetized (Heijo Box, Heijo Research Electronics, UK; see Figure 3). The maximum finger contact area was about 2-4 mm. The eight actuators, connected to a 'standard' PC via parallel port, were controlled by a purpose-written Matlab program in combination with the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). Participants' responses were recorded via foot pedals. In the practice phase, visual information such as instructions, fixation cross, and response feedback, was video-projected onto a semi-transparent Plexiglas table (size, 70 x 60 cm; height, 84 cm) by a projector (Sharp XR-32X-L), therefore available to participant's monitoring. In the experimental phase, a blindfold was used to prevent participants from seeing the tactile arrangements (and thus avoiding visual learning of tactile arrays). Further, vibro-tactile stimulations were masked by white noise (1000 Hz, ~65 dBA, 3000 ms or until response execution) delivered via cushioned ear shells headphones (Philips SHL4000, 30-mm speaker drive). This was again done in an attempt to rule out confounding factors in the determination of participants' performance, such as auditory learning of tactile arrays: note that different vibro-tactile stimulations generate different tones, thus potentially offering an additional auditory source of information for configural learning.

Procedure Following written and verbal instructions, participants were equipped with headphones, and, once comfortably seated on a chair with their forearms on the table, gently placed their fingertips (except the thumbs) on the stimulators. Prior to the practice session, the positions of the stimulators were adjusted to fit participant's fingers. In order to maximize comfort, participants chose whether or not they wanted to use a cushion as a wrist-rest throughout the experiment.

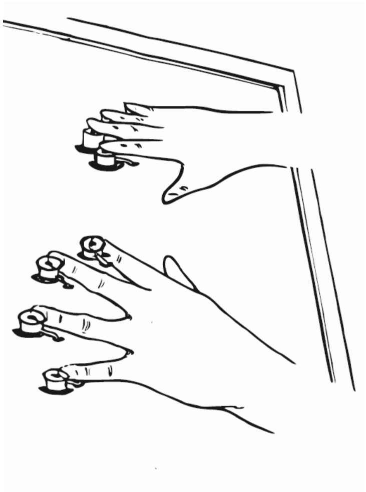

Figure 3 Illustration of the experimental set-up. Participants placed their fingers (except the thumbs) on eight solenoids delivering tactile stimulation. The solenoids are indicated by the rings in the figure. In Experiments 1 and 2, participants indicated the location of a feature-singleton target defined by a different frequency relative to the distractors, as being delivered to a left- or a right-hand finger by pressing the corresponding (left or, respectively, right) foot pedal. In Experiment 3, participants indicated target identity using the appropriate foot response regardless of the hand or finger stimulated.

Practice session Each trial of the practice session started with a foot press, and included stimulations delivered to seven distractor fingers vibrating at 100 Hz, and one target finger vibrating at 30 Hz. All stimulators vibrated until a response was made or up to 3000 ms, whichever came first. In doing so, the target was presented four times at any of the eight fingers, yielding 32 practice trials in total. Note that, given the limited number of tactile configurations available for the experimental session (see below), the practice session used stimulations of all eight fingers. The idea was to familiarize participants with the tactile search task, that is: target vs. distractor discrimination in general, rather than the learning of specific tactile arrangements. Participants' task was to localize the target, as fast as possible, on the left or the right hand by pressing the spatially corresponding foot pedal. Following participants' response, accuracy feedback was provided by presenting the words "correct" or "wrong" on the Plexiglas plate (duration: 1000 ms). Participants were instructed to monitor this feedback and use this to improve their tactile search performance. Thus, emphasis was placed on both response speed and accuracy.

<u>Experimental session</u> Following instructions, participants started the experimental session by a foot press. Both tactile vibration and white auditory noise were presented simultaneously until a response was made or up to 3000 ms. Importantly, unlike the practice session, in the experimental session, participants were wearing a blindfold so that they did not see their fingers, thus preventing concomitant visual learning of repeated tactile arrangements. Participants were asked to respond to the target side (either the left or the right) as fast and as accurately as possible by pressing the corresponding foot pedal. The next trial was automatically initiated following an inter-trial interval of 1000 ms.

<u>Design</u> The design of Experiments 1-3 was adapted from Chun and Jiang (1998). On each trial of the experimental session, the tactile configuration consisted of stimulations of one target and three distractor fingers. To balance vibro-tactile stimulations between the two hands, a given tactile configuration always involved one hand with two distractors, and the other hand with one distractor and one target (see Figure 4). A set of four Old configurations was

randomly generated for each participant. For these Old configurations, the relationship between target and distractors was kept constant throughout the entire experiment (a block consisted of a set of four Old plus four New configurations). The New configurations, by contrast, were newly generated in each block by distributing the three distractors anew across the remaining fingers of each hand on each new trial. Importantly, in the New condition, too, the four target fingers were held constant throughout the experiment. Thus, four fingers were used for targets in the Old configurations (two fingers of each hand) and four fingers for the New configurations (again two fingers of each hand). In doing so, participants had no bias to search for a target at specific fingers, since each finger was equally likely to contain a target. Performance gains in the Old condition could therefore only be attributed to the effects of repeated tactile arrangements, rather than repeated absolute target locations. The latter was equated across the Old and New tactile conditions. The experiment consisted of 128 trials, divided into 16 blocks. At the end of every second block, white noise was interrupted, followed by the presentation of a brief double beep (2 x 200 ms, 1000 Hz, ~72 dBA; separated by an 800 ms silent interval), indicating that participants could take a short break, and resume the experiment (by a foot press) whenever they were ready to continue. The entire experimental session lasted about 30 minutes.

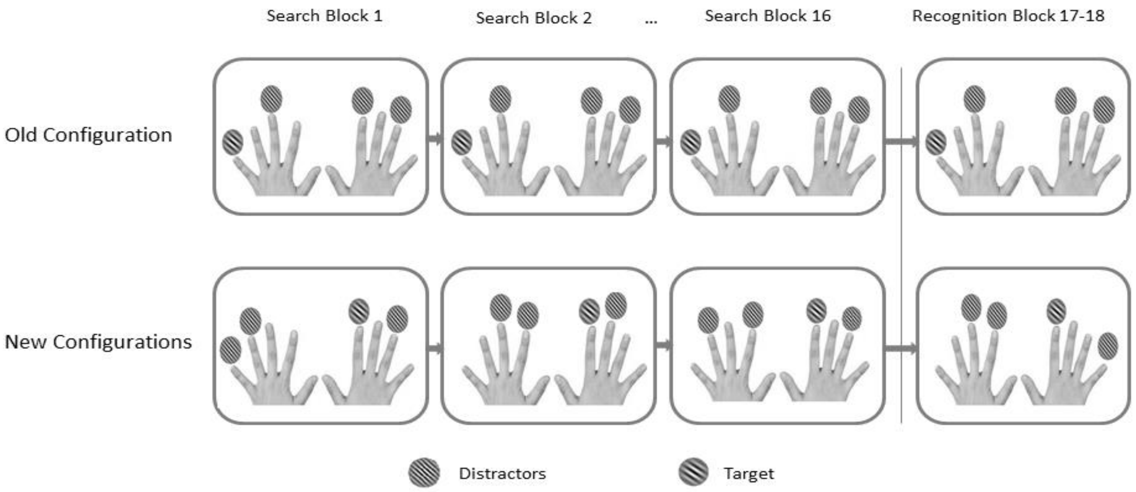

Figure 4 Schematic figure displaying the distribution of items in Old and New configurations across search epochs (and the recognition task for Experiments 2 and 3). In Old configurations, the target location is constant and paired with constant distractors locations; in New configurations, by contrast, only the target location is held constant across repetitions.

Results

In order to increase statistical power, the data of two consecutive blocks were pooled together into one epoch (see Chun & Jiang, 1998), resulting in 8 experimental epochs. For RTs, trials in which participants made an erroneous response or RTs were below 200 ms or above 3000 ms (i.e., when no response was made) were excluded from analysis (overall 10.5% of trials). The error and RT data were examined in repeated-measures ANOVAs, with effects Greenhouse-Geisser corrected when sphericity was violated.

<u>RT performance</u> A 2 x 8 factorial repeated-measures ANOVA on the RTs revealed a significant main effect of configuration, F(1,8) = 8.29, $p < .05$, $\eta_p^2 = .509$: targets embedded in Old configurations were detected significantly faster than those embedded in New configurations (849 vs. 952 ms), indicative of a tactile contextual-cueing effect (of 103 ms)[1]. Further, RTs were relatively constant across experimental epochs (non-significant effect of epoch, F(7,56) = .469, p = .673). Although the configuration x epoch interaction was non-significant, F(7,56) = .737, p = .642, additional t-tests showed that there was no difference between RTs for Old and for New configurations in epochs 1 and 2 (both p > .2; see also Figure 5). From this, one can conclude that reliable tactile contextual-cueing developed over the course of the tactile search task.

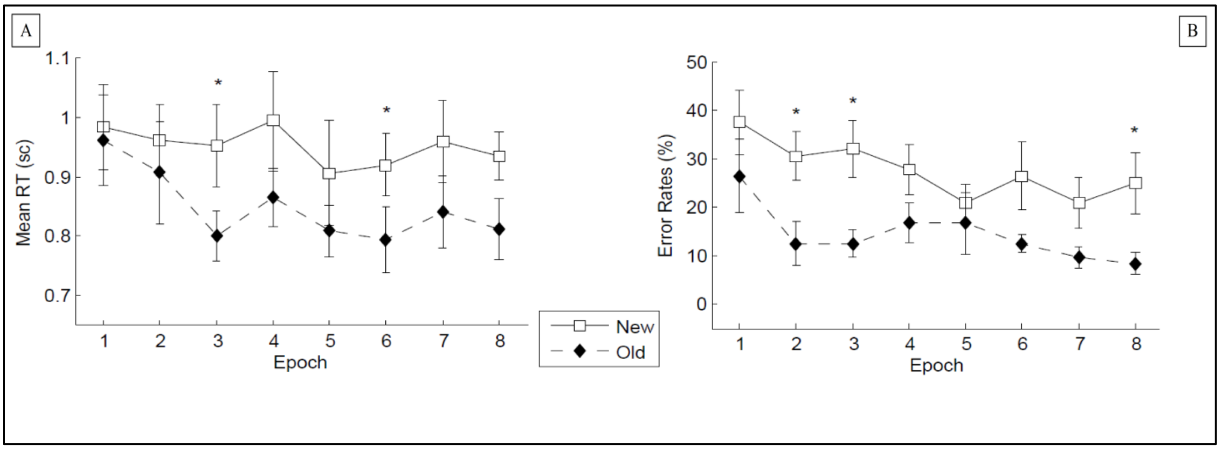

Figure 5 Experiment 1—Mean response times across epochs for Old and New configurations (A), with error bars representing within-participants' standard errors of the mean (Cousineau, 2005). Mean error rate across epochs, separately for Old and New configurations (B), with error bars representing the standard error of the mean. (* = p< .05; ** = p<.01, *** = p<.001)

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[1] Note 1. In a control analysis we examined the variability in distractor locations, measured as the standard error (SE) of RTs, in Old and New configurations. It is possible that at least parts of the RT difference between the two types of configurations can be attributed to larger variability in distractor positions in new configurations (in addition to contextual cueing of haptic search in old configurations). However, a t-test comparing SE's between New and Old configurations was non-significant: t(8)=1.39, p = .202. Similar results were obtained for Experiment 2 (t(11) = .000, p = 1.00) and Experiment 3 (t(13) = 1.52, p = .15). This rules out the alternative account.

Error analysis A 2 x 8 factorial repeated-measures ANOVA on the error rates with configuration (Old vs. New) and epoch (1-8) as factors failed to reveal a significant effect of configuration, F(1,8) = 3,85, p = .08, η_p^2 = .325. Because errors made in New configurations (13.80%) were almost twice as high as those made in Old configurations (7.20%), we run an additional (two-tailed) t-test comparing RTs between Old and New response error trials in order to examine for any possible speed-accuracy trade-off (SATO) in the data. This test failed to reveal a significant effect of configuration, t(8) = 1.24, p = .247. Furthermore, the ANOVA revealed the effect of epoch to be significant, F(7,56) = 2.31, p < .05, η_p^2 = .225, reflecting a decrease in the number of errors as the experiment progressed. The interaction between configuration and epoch did not reach statistical significance, F(1,7) = .569, p > .778.

Discussion

Experiment 1 employed a tactile search task in order to test whether tactile spatial context can be learned under exclusively tactile search conditions. The results provide clear evidence for this hypothesis. First, RTs were faster in Old compared to New tactile arrangements, an effect that became reliable after three epochs of learning (i.e., after 5-6 repetitions of each tactile configuration). Second, fewer response errors were made in Old compared to New tactile configurations (although this effects was non-significant) and the higher error rate in the latter condition was not due to a SATO. Nevertheless, response errors in both conditions decreased as the experiment progressed as observed in a main effect of epoch on response accuracy. Altogether, Experiment 1 provides evidence for context-dependent tactile learning, reflected by faster RTs in Old relative to New tactile arrangements and (numerically) fewer response errors to Old arrangements. Context-independent, procedural learning was also observed, reflected by a general reduction of the error rates across experimental epochs.

A highly debatable claim in *visual contextual-cueing* is whether the effect is supported by implicit memory (for a critial discussion see, e.g., Schlagbauer, Müller, Zehetleitner, & Geyer, 2012 or Smyth & Shanks, 2008). Although Experiment 1 provided clear support for contextual-cueing of tactile search, it leaves open the question of the implicit nature of the tactile contextual-cueing effect. To address this issue, Experiment 2 introduced a recognition test at the end of the experimental session to examine whether participants have awareness of the repeated tactile configurations.

Experiment 2

Method

Experiment 2 was a close replication of Experiment 1 with the following exceptions. In addition to implementing a recognition test, Experiment 2 implemented a more conservative practice regime with the aim of reducing the relatively high rate of response errors made by participants in Experiment 1 (New configurations: 13.80%; Old configurations: 7.20%). To this end, in Experiment 2, participants were informed that they would proceed from the practice to the experimental session only after having attained a minimum of 80% correct responses in the practice session.

Participants Fourteen new participants took part in Experiment 2 (7 females, 13 right-handed, age range 19 to 34 years). The criteria for participation, payments, and ethical guidelines were the same as Experiment 1. Two participants were excluded because they showed unusually large contextual-cueing effects already in the first experimental epoch. A post-hoc analysis revealed that for these two participants, just by chance, target fingers in Old and New configurations were chosen in such a way that they were symmetrically allocated across hands, with Old targets being presented at fingers 2 and 4 and New targets at fingers 1 and 3 of the left and right hand, respectively. This may have fostered the coupling of targets with specific (Old, New) distractor arrangements. The proportion of trials excluded due to incorrect responses was 6.70%. Outliers occurred in 0.06% of all trials (i.e., RTs below 200 ms and above 3000 ms).

Procedure Practice session: In addition to visual feedback, incorrect responses triggered an “error warning” beep (2500 Hz, ~85 dBA, 900 ms), followed by a silent inter-trial interval of 2000 or 2500 ms. Furthermore, overall accuracy feedback was provided visually by displaying to participants their mean correct response rate after every second practice block (of 16 trials). Participants were asked to aim for a minimum of 80% correct in at least 3 consecutive practice blocks. The experimental session was similar to Experiment 1, except for the use of “error warning” beeps following response errors. The entire experimental procedure lasted about 30-40 minutes.

Recognition task At the end of the experimental session, participants performed a “yes-no” recognition task, meant to assess their explicit knowledge of repeated tactile configurations. The recognition test consisted of 16 trials: 4 x 2 Old and 4 x 2 New configurations, presented in randomized order, with the exception that a given display was never shown repeatedly on two consecutive trials. Because each Old configuration was presented twice, each New configuration was also presented twice in order to equate repetition effects across the two types of configuration.

Results

RT performance A 2 x 8 factorial repeated-measures ANOVA on the RTs revealed a significant main effect of configuration, F(1,11) = 6.02, p < .05, η_p^2 = .354: targets embedded in Old tactile arrangements were responded to faster than targets in New configurations (775 vs. 885 ms), resulting in a contextual-cueing effect of 110 ms. No other effects reached statistical significance; epoch F(7,77) = 2.24, p = .14, and configuration and epoch interaction F(7,77) = .853, p = .547. Regarding the non-significant interaction, additional t-tests showed that there was no RT difference between Old and New configurations in epochs 1 and 2 (p > .1; see Figure 6). This outcome suggests that, as in Experiment 1, tactile contextual-cueing developed as the experiment progressed.

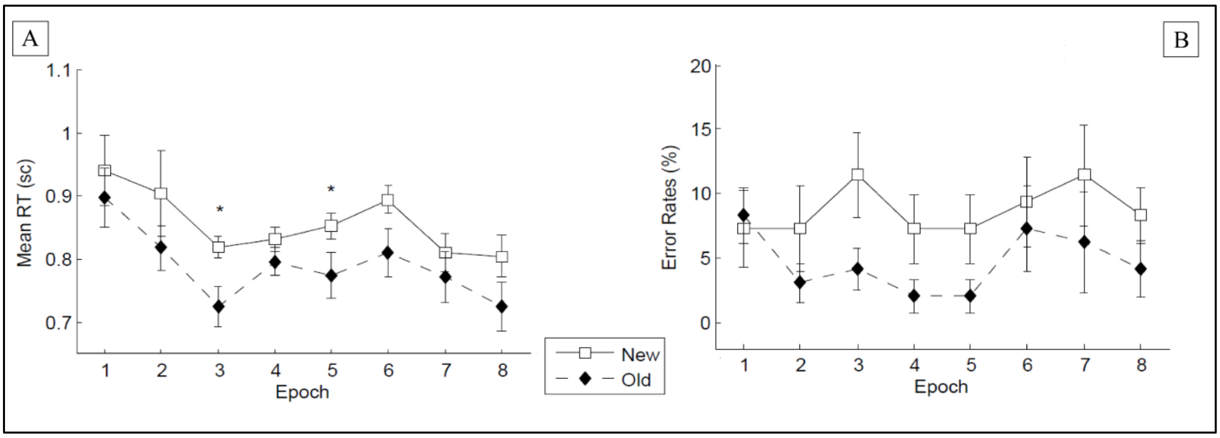

Figure 6 Experiment 2—Mean response times (A), and error rates (B). See figure 3 for information about error bars and star signs. (* = p< .05; ** = p<.01, *** = p<.001)

Error analysis Similar to Experiment 1, a 2 x 8 factorial repeated-measures ANOVA on response accuracy failed to reveal a significant effect of configuration F(1,11) = 3.32, p = .09 as participants again made fewer errors when searching for targets in Old (2.34%) than in New configurations (4.36%). A further t-test comparing the RTs on error trials between Old and New configurations was performed. Once again the t-test failed to reveal a significant effect of configuration, t(8) = 1.75, p = .117, again ruling out a SATO. No further effect reached statistical significance: epoch, F(7,77) = .662, p = .703; configuration x epoch interaction, F(7,77) = .581, p = .769.

Recognition performance Recognition accuracy was assessed based on the signal detection-theoretic measure d' (Green & Swets, 1966). For each participant, d' was computed, taking into account participants' hit rates (correct judgment of Old configuration as repeated) and false alarm rates (incorrect judgment of New configuration as repeated). An explicit effect would be indicated by d' being significantly greater than zero. However, across all participants, d' was quite low (.314) and statistically indistinguishable from zero, t(11) = 1.81, p = .09, suggesting that tactile contextual-cueing is an implicit effect.

Discussion

Experiment 2 replicated the tactile contextual-cueing effect found in Experiment 1, thus corroborating the idea that participants can learn repeated target-distractor arrangements in tactile search. Interestingly, the extensive practice reduced drastically the response errors in the experimental session (Experiment 2 vs. Experiment 1 - Old: 2.34 vs. 7.20%; New: 4.36 vs. 13.80%). Notably however, even after such a marked reduction of response errors, fewer error responses were still made to targets presented in Old than in New arrays. Finally, and of the greatest importance, the results of the recognition test suggest that memory for Old configurations is implicit, as participants were unable to tell apart Old from New configurations.

One objection to Experiment 2 (and Experiment 1) may be that foot responses were always congruent with the target hand. That is, after detecting an odd-one-out tactile stimulus at the fingers of a given (i.e., the target) hand, it is conceivable that the corresponding foot pedal could be pressed ‘automatically’. In other words, the RT benefit for Old compared to New tactile arrangements might reflect context-based facilitation of stimulus (i.e., hand) to response mapping (for the sake of simplicity, we will refer to this as ‘response hypothesis’), rather than, or in addition to, contextual-cueing of target selection (‘attention hypothesis’). To disentangle these alternative hypotheses, Experiment 3 introduced a discrimination task (as opposed to the localization task in Experiments 1 and 2), in which participants had to first detect and subsequently discriminate the waveform of the target signal. That is, foot pedals were associated with the target waveform, rather than the target hand. Under these conditions, the response hypothesis would predict no RT advantage for Old vs. New tactile contexts, whereas the attention hypothesis would still predict a benefit for Old arrangements.

Experiment 3

Method

Experiment 3 was similar to Experiments 1 and 2, except that it used a discrimination task. Further, a new practice session was implemented in order to familiarize participants with the two different target signals.

Participants 14 new participants took part in Experiment 3 (9 females, 12 right-handed, age range 21 to 30 years). The criteria for participation, payment, and ethical guidelines were the same as in Experiments 1 and 2. Of all participants, only one did not provide data for the recognition test, owing to technical issues. The proportion of trials excluded due to incorrect responses was 9.3%.

Apparatus and Stimuli In order to create (three) distinct signals for targets (2 signals) and distractors (1 signal), the solenoid actuators were controlled by a new, 10-Channel Tactor Amplifier (Dancer Design) connected to a standard PC equipped with a National Instrument Card (NI PXI-1042Q). The two possible tactile targets, T1 and T2, were defined by a square waveform manipulation on 150 Hz vibrations (Figure 7); distractors, by contrast, were constant 150-Hz vibrations.

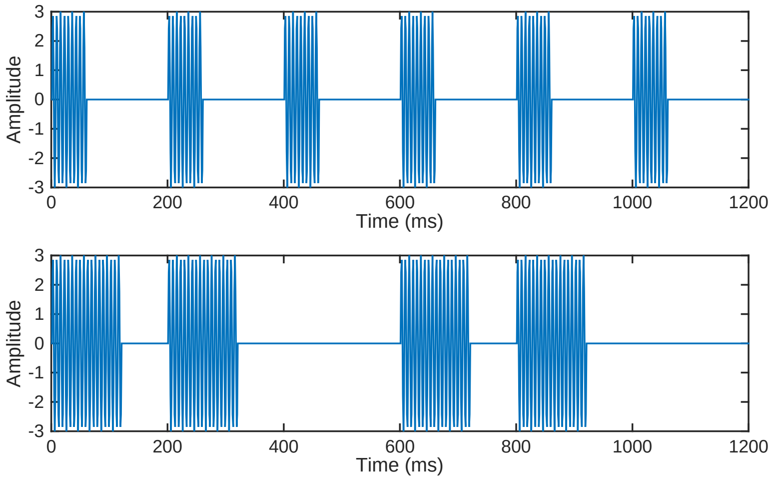

Figure 7 Waveforms of two tactile targets. The upper panel indicates the waveform of Target 1 (T1), a 5-Hz square wave with 30% duty cycle delivered via 150-Hz vibrations. The lower panel shows the waveform of Target 2 (T2), a burst square wave (mean frequency of 4.17 Hz) with an average 30% duty cycle delivered via 150 Hz-vibrations. The distractors are constant vibrations of 150 Hz.

Procedure The practice session was divided in two parts. In the first part, participants learned the identity of the two possible targets. One target was presented in isolation per trial in a randomized fashion on each finger of each hand (except the thumbs). Furthermore, because the features of each target were rather technical for written or verbal instructions, in the first 16 trials of the practice participants received a visual cue informing participants about the identity of the current target “T1” or “T2”, so they could learn the physical properties and the appropriate foot response. In the second half of the practice session, participants trained the tactile search task with one target and seven distractors (similar to Experiments 1 and 2; no visual cues about the target identity were given). Participants were instructed to respond as fast and as accurate as possible, within 3000 ms. Participants received “error warning” beeps and the inter-trial intervals after erroneous responses. Of note, progress from the first to the second part of the practice session and from the practice to the test session was only possible when participant achieved 80% accuracy in each of the two practice phases. Target pedal assignment was counterbalanced across participants: half of participants used the left (right) foot pedal for “T1” (“T2”) and vice versa for the other half. The entire experimental session lasted 30-50 minutes, depending on participants’ performance in the training session.

Recognition task At the end of Experiment 3 participants performed “yes-no” recognition test similar as in Experiment 2.

Results

RT performance A 2 x 8 factorial repeated-measures ANOVA on the RTs revealed a significant main effect of configuration, F(1,13) = 5.95, $p < .05$, $\eta_p^2 = .314$: discrimination was faster for targets embedded in Old tactile configurations compared to New configurations (1373 vs. 1416 ms), indicative of a tactile contextual-cueing effect (of 43 ms). No further effect was significant: epoch, F(7,91) = 2.55, p = .08; configuration x epoch interaction, F(7,91) = .567, p = .781. Regarding the non-significant interaction, additional t-tests revealed the RT difference between Old and New configurations to become significant only late in the experiment, in epoch 6 ($p < .05$; see Figure 8).

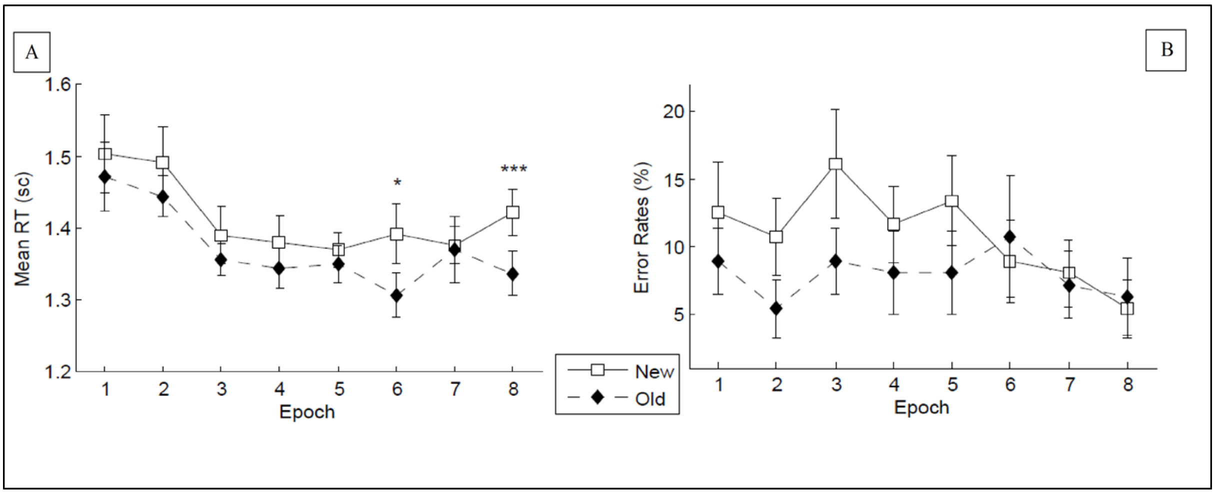

Figure 8 Experiment 3—Mean response times (A), and error rates (B). See figure 3 for information about error bars and star signs. (* = p< .05; ** = p<.01, *** = p<.001)

Error analysis A 2 x 8 factorial repeated-measures ANOVA on response accuracy failed to reveal a significant effect of configuration, F(1,13) = 2,49, p = .138. However, because participants made fewer errors when searching in Old (3.9%) as compared to New configurations (6.36%), a further t-test comparing the error RTs between the two conditions was performed. The analysis failed to reveal a significant effect of configuration, t(11) = 1.61, p = .134, once again ruling out a SATO in the determination of the RT results. No further effect was statistically significant: epoch, F(7,91) = .139, p = .251; configuration x epoch interaction, F(7,91) = .681, p = .688.

Recognition performance Across all participants, d' was quite low (-0.17) and statistically indistinguishable from zero, t(13) = -1.29, p = .218. This result further supports the findings of Experiment 2, namely, that tactile contextual-cueing is mediated by implicit memory representations.

Discussion

Experiment 3 examined whether RT benefits for Old vs. New tactile configurations were due to facilitated (learnt) stimulus-to-response mappings or facilitated target selection. Employing a target discrimination task – in which different vibro-tactile stimuli (T1 and T2), each of which could occur in both hands, were mapped to the foot responses –, RTs were found to be still faster for Old tactile arrangements. This largely rules out that the reduced RTs for repeated tactile-search arrangements are attributable to facilitation of response selection. Instead, the finding of an RT benefit for Old arrangements strongly supports the alternative view of tactile contextual-cueing facilitating attentional target selection (rather than post-selective stimulus-to-response mapping). The analysis of error rate revealed no significant differences between Old and New configurations. However, as in Experiments 1 and 2, if anything there was an (numerical) accuracy advantage for Old vs. New tactile arrangements in Experiment 3 – that is, here: greater accuracy in discriminating, rather than localizing, the target in Old configurations. This further supports the idea that configural learning did aid attentional target selection and, thus, subsequent (post-selective) processes of focal-attentional target discrimination. Finally, the results of the recognition test corroborate the idea that tactile contextual-cueing is supported by an implicit memory, as participants were not able to tell apart Old from New configurations.

It should be noted that the results of Experiment 3 do not rule out potential contributions of response selection to the RT advantages for Old arrangements in Experiments 1 and 2. In fact, in Experiments 1 and 2, contextual-cueing was twice as large as in Experiment 3 (103, 110, and 43 ms in Experiments 1, 2, and 3, respectively). It may well be that the reduction of the effect in Experiment 3 reflects the fact that the perfect coupling of hands and foot pedals (and learning of the couplings for repeated arrangements) in the previous experiments contributed to the overall RT advantage for Old arrangements. Given that such a contribution was effectively ruled out in Experiment 3 (by making the coupling inconsistent), the tactile 'contextual-cueing' effects in Experiments 1 and 2 is likely to represent an additive mixture of both facilitation of target selection and facilitation of response selection. This 'hybrid view' would suggest that contextual-cueing can exert a boosting influence on both target and response selection, consistent with Kunar, Flusberg, Horowitz and Wolfe (2007), who argued for such view in relation to visual contextual-cueing.

Note that, in the present study, we inferred the effect contextual-cueing on attentional selection only indirectly, by comparing the Old vs. New configuration effects between discrimination and a localization task. Thus, ideally, this evidence should be followed up in a more direct test, involving a set size manipulation or a direct measure of brain-electrical (EEG) activity indexing the allocation of attention. Such direct tests are, however, beyond the scope of the current study, especially as they would introduce new challenges, such as whether a set size manipulation is an appropriate means for inferring attentional guidance by contextual-cueing (see, e.g., Kunar et al., 2007, and Kunar, Flusberg, & Wolfe, 2008, for discussion) or which brain region provides an apt electrophysiological signal for context-based guidance in tactile search (one candidate area being the somatosensory cortex; cf. Eimer et al., 2002). In the meantime, though, the important observation remains that tactile contextual-cueing was reliable in a discrimination task, where there was no consistent hand (configural pattern) to foot mapping. This strongly suggests that response selection cannot be the sole source of the contextual-cueing effect. Instead, the effect also involves a component of attentional guidance.

General Discussion

The present study aimed at answering two questions: First, can contextual-cueing arise from repeated exposure to purely tactile search configurations? And second, is tactile contextual-cueing an implicit effect? Three experiments were conducted to answer these questions. The aim of Experiment 1 was to test whether contextual-cueing, an effect hitherto examined almost exclusively in the visual domain, would also operate in tactile search. Experiment 2 was, additionally, designed to assess participants' explicit knowledge of repeated tactile configurations. And Experiment 3 aimed at dissociating the effects of Old (vs. New) tactile arrangements on attention and response selection. The results were as follows: response speed and accuracy were improved for Old relative to New configurations in all three experiments, indicating that memory for repeated tactile configurations is acquired and subsequently expressed in tactile search. Further, participants' ability to distinguish Old from New configurations was only at chance level, indicative of tactile contextual-cueing being supported by an implicit memory system (Experiments 2 and 3). Moreover, contextual-cueing was observed to be sufficiently strong to aid performance even in a target discrimination (rather than just only in a target localization) task (Experiment 3). Taken together, these findings show that the tactile system is able to develop its own context representations and use these representations to guide tactile search. Further, the build-up of memory for repeated tactile configurations is an automatic process, in that it does not require explicit knowledge of any repeated configurations.

To our knowledge, the present findings are the first to show that invariant spatial configurations presented exclusively to the tactile modality can be learned and subsequently facilitate tactile search. To date, only one study has demonstrated effects of learnt configurations (context) in tactile search. According to Nabeta et al. (2003), contextual knowledge acquired solely within the visual modality can subsequently facilitate haptic search. However, as pointed out in the Introduction, the results of Nabeta et al. are open to alternative interpretations, such as haptic contextual-cueing being mediated by a visuo-spatial representation that may trigger learned visual context associations to guide haptic search. Most importantly, Nabeta et al. (2003) did not directly address the issue of whether haptic contextual cues can be learned when repeated target-distractor configurations are presented exclusively to the haptic modality. Concerning this issue, our findings unequivocally show that contextual-cueing develops when sighted, but blindfolded participants are required to discriminate the location or identity of a feature singleton target in tactile search.

The current design endeavoured to implement the essential features of the visual contextual-cueing paradigm – in particular, presentation of repeated configurations in half of the trials (Chun & Jiang, 1998; Chun, 2000; Conci, et al., 2013; Geyer et al., 2013; van Asselen & Castelo-Branco, 2009). Nevertheless there are limitations that prevent a direct comparison between the current tactile and the ‘standard’ visual paradigm. In visual contextual-cueing, items are distributed across a relatively large display area with a large number of possible locations, for example, 6 x 8 locations in Chun and Jiang’s (1998) study. Moreover, a typical configuration consists of 12 items, one of which is the target “T” and the 11 others distractors being “L’s”. A few studies also used smaller set sizes of 4 items, larger sizes of 16 items, or manipulated set size actively in an attempt to investigate the effects of contextual-cueing on the efficiency of attentional selection (e.g., Annac et al., 2013; Chun & Jiang, 1998; Kunar et al. 2008; Makovski & Jiang, 2010). Accordingly, the number of possible item configurations is quite large, ranging up to thousands of configurations in a given experiment.

In the current tactile version of the contextual-cueing paradigm, by contrast, manipulation of set size was not possible; instead, it was fixed at four items, comprising of one target and three distractors on each trial. The set size and item features are tightly restricted owing to a few crucial reasons, including: the limited number of possible item locations (8 fingers), low vibro-tactile discrimination sensitivity (Lederman & Klatzky, 2009), and device limitations. Due to those limiting factors, the number of possible tactile configurations reduces dramatically. In an attempt to make the paradigm more similar to visual contextual-cueing, the number of trials in tactile search could, in principle, be increased by producing different vibro-tactile patterns to generate different distractors (in the, nevertheless, same configurations). Arguably, however, this would come along with the cost of making the task considerably more difficult to perform. Recall that in the current set-up, although the target was a feature singleton (rather than a conjunction target, as used in the standard visual paradigm), response errors occurred in a high proportion of trials, even after participants had extensively practiced the task.

Finally, again considering the limitations in implementing a practicable tactile contextual-cueing paradigm, some results lack statistical power, particularly those of the recognition tests: recall that the test comprised of only 16 trials. However, this argument would also apply to almost all visual contextual-cueing studies, as they typically use (visual) tests that are rather short (even though there are no obstacles to conducting longer tests; see, e.g., Smyth & Shanks, 2008, and Schlagbauer et al., 2012, including a discussion of power problems in explicit tests of contextual-cueing). Central to the limitation in the current type of (tactile) set-up in tactile search is again the set size problem, which should be addressed in the future.

Despite of the above limitations, our results provide an initial understanding of the independent capacity of the tactile modality as permitting invariant spatial configurations to be extracted and stored in terms of long-term memory representation that may be activated by currently encountered tactile configurations and thus guide tactile search – quite similar to visual contextual- cueing (Chun & Jiang, 1998). Consequently, this demonstration lends itself to addressing a number of new important questions concerning tactile contextual-cueing. In particular, with reference to crossmodal cognitive processes, it would be of prime importance to investigate whether spatial regularities learned in the tactile modality could also facilitate visual search and vice-versa. Due to the limited available evidence on crossmodal implicit spatial learning, it is not yet clear whether configural representations that are formed modality-specific are also shared across multiple – namely, visual and tactile – sensory domains. For example, Newell, Woods, Mernagh and Bülthoff (2005) found that both visual and haptic representations (of seven wooden animals presented in front of the participant) were dependent on the position of the participant through encoding, suggesting that both representations are supported by a viewer-centered reference frame. However, when participants had to judge on which two of seven objects were in new positions, accuracy performance was higher in the intra-modal (e.g., visual-visual) relative to the crossmodal (e.g., haptic-visual) conditions. Note that in Newell et al. (2005) the experiments were divided into a training phase (intended for the acquisition of either a visual or haptic representations) and test phase (intended for the expression of these representations). Their results suggest that encoded representations contain not only information about the orientation of the scene, but also about the encoding modality. That is, objects experienced visually or haptically in an explicit learning task form their own spatial representations. The results of the current experiments support the notion that (tactile) contextual-cueing can originate from repeated encounters of tactile search configurations, making the question of the modality-dependent vs. -independent memory representations in contextual-cueing, and implicit perceptual learning in general, an interesting issue for future investigations.

In summary, the present study shows that tactile configural regularities can be learned and subsequently guide tactile search, and that this process is rendered implicit. This finding provides the first evidence that powerful “implicit memory” mechanisms allow specific tactile information to be retained from the sensory environment and to persist over time. These implicit memory traces contribute to the guidance of attention in the real-time processing of the perceptual array, making processing efficient by reducing the need for capacity-limited, top-down controlled mechanisms.

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Study II: Reference frame of tactile contextual-cueing

Contextual-cueing of tactile search is supported by an anatomical reference frame

Summary

The second study of this Thesis concerns the reference frames used to code learned context cues in a tactile search task. Reference frame determines where to direct attention when a repeated display is encountered in subsequent occasions. In the tactile domain this issue is not a trivial one because effectors (e.g., limbs) can move within a certain space near the body, in some cases causing a conflict when say, a tactile stimulus is presented on the right hand (somatotopic reference frame), with this hand occupying the left hemispace (external reference frame) in a crossed limb position. However, while tactile reference frames have been investigated in various paradigms such as the temporal order judgement, Simon effect, and inhibition of return to name a few, it is an open question whether shifts of attention in a learned tactile arrangement are supported by a somatotopic or external reference frame. As opposed to the aforementioned tactile tasks that required that the information is stored for rather short periods of time lasting only milliseconds, tactile contextual-cueing is long-lasting and supported by other forms of (long-term) memory. In Study II, we administered the tactile contextual-cueing task in a learning and test session. First, in order to investigate whether the effect was generally coded in a somatotopic or external reference frame, participants learned tactile environmental context with their limbs crossed (uncrossed) in a learning session. Subsequently, in a test session the participants performed the search task with the uncrossed (crossing) limbs. In the somatotopic condition, learned arrangements (from training) were presented in a way that the fingers containing the target and distractors were identical across both sessions. In the external condition, by contrast, the locations of the target and the distractors in learned tactile configurations were kept constant in environmental coordinates across the sessions. The findings showed that tactile contextual-cueing was coded in a somatotopic reference frame, as contextual learning was only transferred from learning to test session when configurations were always presented at identical finger locations across training and test. Second, and in order to investigate external hand-centered vs. anatomical-skin based representation of the tactile cueing effect, in Experiment 2 of this Study, participants performed a learning session with the hands stretched out in a parallel position. In the test session, participants flipped their hands up (down) by 180˚. In the somatotopic-skin centered condition, configurations were presented to same fingers across both sessions, whereas when configurations were fixed in external hand-centered coordinates, the target and the distractors in repeated tactile contexts, although staying at the same external coordinates with respect to a given hand, appeared at different fingers across the sessions. This design showed that a skin-based reference frame supports context learning. Contextual facilitation was only significant in a test session when configurations were presented to the same fingers across sessions. While cueing was reversed when configurations were kept stable on a hand-external reference frame. We concluded that TCC is coded in an a somatotopic reference frame. Moreover, these findings add to the current literature on spatial representations in tactile perception that has hitherto been almost exclusively studied in tasks requiring transient forms of memory rather than long-term memory. Assuming that the current tactile search task requires observers to monitor their body (fingertips), this could have led to an anatomical reference frame, whereas other tactile tasks requiring observers, e.g., to execute a movement, may recruit an external reference frames. It therefore appears that the reference frames of tactile perception are adaptive and sensitive to task demands.

Abstract

This work investigates the reference frame(s) supporting ‘tactile contextual-cueing’. In tactile search with the fingers, if a searched-for target object is repeatedly encountered within a stable spatial arrangement of task-irrelevant distractors, detecting the target becomes more efficient over time (relative to non-repeated arrangements), because learned target-distractor spatial associations come to guide tactile search, thus cueing attention to the target location. Since spatial representation of search items can be coded in external or/and one’s own body reference frame, we asked whether the guidance of attention from tactile memory is supported by: i) an external or an anatomical hand-based reference frame (Expt. 1), and ii) concerning the latter, whether the anatomical representation is coded in hand-centered external, or anatomical skin-based reference frame (Expt. 2). Observers performed a tactile search task, divided into a learning and test session. At the transition between the two, we introduced postural manipulations of the hands (crossed vs. uncrossed in Expt. 1; palm-up vs. palm-down in Expt. 2) to determine the reference frame of tactile contextual-cueing. Target-distractor associations acquired during learning transferred to test only when the placement of the target and distractors was held constant in anatomical hand-based reference frames (Expt. 1) or skin-based reference frames (Expt. 2). We conclude that tactile contextual learning is supported by an anatomical, skin-based reference frame.

Introduction

Perception in visual and tactile context

Humans exhibit an impressive capacity for detecting regularities in complex, multi-sensory arrays. The mechanism behind this is referred to as statistical, implicit learning: memory about repeated patterns acquired incidentally facilitates shifts of attention towards relevant perceptual attributes, improving object recognition and visual selection (Jiménez, 2003). In recent years, statistical learning has been extensively studied using the contextual-cueing paradigm (e.g., Chun & Jiang, 1998). In this paradigm, participants perform a relatively difficult search for a target letter "T" embedded in a set of distractor letters "L". Unbeknownst to them, half of the trials contain repeated displays, while the spatial arrangement of the target and the distractors is compiled anew in the other half of trials (non-repeated displays). The standard finding is that reaction times (RT) are faster to repeated compared to non-repeated displays, an effect referred to as contextual-cueing (CC = non-repeated mRT – repeated mRT). What is more, participants' ability to discriminate repeated from non-repeated displays is typically only at chance level. Chun and Jiang (1998) took these findings to mean that learned spatial target-distractor associations, stored in implicit long-term memory, come to guide the search, cueing attention to the target location.

It worth noting however, that context-based facilitation of search is not limited to the visual modality. As an instance, a recent study showed reaction time benefits for incidentally learned contextual cues in a tactile search task (i.e., tactile contextual-cueing effect – TCC; Assumpção, Shi, Zang, Müller, & Geyer, 2015a; see also Nabeta, Ono, & Kawahara, 2003). Assumpção and colleagues (2015a) asked blindfolded participants to search for a tactile target that could be embedded in either repeated or non-repeated target-distractor arrangements. On each trial, four fingers (one target, three distractors; a target was always present) were stimulated simultaneously, two on the left and two on the right hand. Participants' task was to localize or discriminate the target by giving foot-pedal responses. In the repeated condition, the target and the three distractors of a given spatial configuration were repeatedly stimulated on the same locations across blocks. By contrast, to equate target location repetition effects across the repeated and non-repeated conditions only the location of the target repeated in non-repeated configurations. It was found that reaction times decreased overall as a function of practice on the task, an effect of procedural learning. Importantly, this decrease was larger for repeated compared to non-repeated configurations, an effect of tactile context learning. Finally, participants were unable to tell apart repeated from non-repeated configurations, indicative of the context memory being implicit in nature. The authors took this set of findings to mean that, similar to visual perception, the tactile modality also has the capability to develop an implicit spatial context representation which facilitates tactile search when the repeated arrays are encountered in later occasions.

Reference frame(s) of tactile contextual-cueing

A fundamental question regarding spatial cognition concerns the reference frames of the underlying spatial representations. In the present context, this issue is important because the reference frame(s) would determine how attention is allocated when a learned (repeated) configuration is encountered in future occasions. Given the recent evidence of the contextual-cueing in the tactile domain (Assumpção et al., 2015a), it is an open issue exactly how tactile search configurations are encoded in tactile memory. That is, what is the reference frame that mediates TCC. The present study aimed at answering this question.

Following on, it is understood that tactile events can be represented relative to where they occur on the body surface or relative to the position of the body (limbs) in external space; henceforth, here we refer to these systems as anatomical versus external reference frames. Prior research has shown that there is a transition from an anatomical to an external frame in the process of generating a manual response: while touch is initially registered in anatomical coordinates, the external representation comes into play later on, especially when participants have to determine the locations of two subsequently presented tactile stimuli (i.e., temporal order judgment - TOJ). This “remapping of touch” (Azañón & Soto-Faraco, 2008; Gallace & Spence, 2005; Schicke & Röder, 2006; Shore, Gray, Spry, & Spence, 2005; Yamamoto & Kitazawa, 2001) has been suggested as a mechanism for goal-directed action, supporting selection of the most appropriate effector (action) for a given task. Applied to tactile contextual-cueing, this could mean that the effect is effector-independent and supported by an external reference frame.

On the other hand, tactile contextual-cueing might also be effector-specific. This idea receives support from studies showing that at least in visual contextual-cueing, stimulus locations are stored in contextual-cueing memory with regard to the exact retinal and / or screen coordinates of the items (i.e., egocentric-viewpoint dependent reference frame; Chua & Chun, 2003). This viewpoint-dependency of visual cueing may arise because environmental regularities (repeated displays) are usually constant across presentations: participants do not have to change their perspective across trials, or move to a different position, and thus could commence their search always from the very same direction. Alternatively, context memory for individual search displays may be by ‘default’ formed for specific vantage points. The reason for this might be that individual search displays are too similar to be recognized by general, viewpoint-independent mechanisms (Tarr & Bülthoff, 1998; recall that , in the standard paradigm, a given search display always consists of one target "T" and eleven distractors "L"), or that repeated search displays are purposefully laid down as individual "snapshots" in context memory. The latter particularly supports viewpoint-dependent scene recognition (see, e.g., Jiang, Swallow, & Capistrano, 2013, for a development of this idea, although using a different spatial learning paradigm). Applied to tactile search, a viewpoint-dependent representation of the search items in tactile context memory would be best characterized by an anatomical reference frame. Of course, both hypotheses are not mutually exclusive in that it is well possible that tactile contextual-cueing is supported by both an anatomical and external frame. This idea receives support from recent behavioural and electrophysiological studies (Buchholz, Jensen, & Medendorp, 2011, 2013; Heed & Roder, 2010; Schubert et al., 2015). These studies commonly suggest that both an anatomical and external reference frame are concurrently available to a given experimental task. Specifically, these studies attribute errors following limb crossing in TOJ tasks to incompatible anatomical and external reference frames, rather than a temporally sluggish transformation process (of an anatomical into an external frame; cf. above). Moreover, these studies attribute an important role in the selection of a given (anatomical vs. external) coordinate system to task factors. Concerning this, Badde and Heed (2016) suggested that a 'focus' on the body determines an anatomical reference frame. Applied to the current tactile task, which required observers to detect a tactile target singleton at the skin surface (fingertips), this could mean that tactile context learning is supported by a body-centered, anatomical reference frame. Thus, the notion of a task-specific use of reference frames would be very similar to the above idea of the operation of a single ('absolute') contextual-cueing reference frame. Given this, both ideas – that of a task-specific use of an anatomical reference frame versus the operation of a single anatomical reference – would support the hypothesis of tactile contextual-cueing being governed by an anatomical reference frame.

In sum, the representation of the body in a complex, multi-sensory environment requires accurate localization mechanisms in order to respond rapidly and adequately to a given tactile stimulation. To achieve this, TCC may be supported by an external, effector-independent reference frame. Alternatively, tactile events may be stored in tactile context memory in terms of anatomical representations, because such representations facilitate the detection of a sensory array as a repeated configuration (with the target location embedded in this configuration). The present investigation was designed to decide between these alternatives.

Overview of Experiments

In two experiments, we investigate the reference frame(s) underlying tactile contextual-cueing. In each experiment, participants performed 16 blocks of tactile search. During which they were blindfolded and received white noise via headphones, so focus was on tactile perception. Tactile stimulators were attached to the four fingers of each hand (except the thumbs). On each trial, four fingers (1 target, 3 distractors) were stimulated simultaneously, two on the left and two on the right hand. There were two potential targets, defined by different frequency amplitude modulations relative to the distractors. One of the two targets was present in each trial. Participants' task was to discriminate the target by using the corresponding foot-pedal (e.g., left pedal for target 1, right pedal for target 2). Unbeknownst to them, half of the trials contained repeated target-distractor arrangements; in the other half arrangements were randomly generated. Each block consisted of eight trials: four repeated configurations and four non-repeated trials. Based on previous investigations (Assumpção et al., 2015a), we predicted faster reaction times to repeated compared to non-repeated configurations (i.e., tactile contextual-cueing effect).

Each experiment comprised a learning (14 blocks) and a test session (2 blocks). At the transition between the two sessions, we introduced changes to hand positions to dissociate external from the anatomical reference frame in (Experiment 1), and hand- centered external reference frame from anatomical, skin-based reference frame (Experiment 2). Experiment 1 used a cross-hand manipulation (see Design section below): half of the participants performed the learning session with uncrossed (crossed) hands and the test session with crossed (uncrossed) hands. Following posture change, search items could either remain stable in external or anatomical coordinates. For example, imagine a participant allocated to the external condition of Experiment 1. She/he will start the learning session with the hands uncrossed. In this specific configuration, the target is presented at the location occupied by the little finger of the left hand. Consequently, for the same configuration in the test session (crossed hands), the target would be presented at the same external location, now occupied by the right index finger. That is, an identical external, but different anatomical representation. The opposite applies to the anatomical condition; a target presented to the little finger of the left (uncrossed) hand in learning session, would again be presented to the same finger in the test session (crossed hands). Thus in the anatomical condition, the item/finger association is kept constant across sessions, however external coordinate changes.

To anticipate the results, Experiment 1 revealed a significant transfer of contextual-cueing in the anatomical, but not the external condition. Experiment 2 further investigated this anatomical tactile contextual-cueing effect. Participants flipped up/down their hands between the learning and test session: half of the group started with downward facing palms followed by upward palms, and vice versa for the other half. There were two conditions: in the hand-centered external condition, the search items were presented to the fingers of the same hand but external coordinates were kept constant across the learning and test sessions. For instance, if the target in a given trial was located on the external space occupied by the left little finger during learning (with palms downward), consequently, in the test session it would be presented to the left index finger, now occupying the same external space (with palms upward). In the anatomical, skin based condition, changes of item positions were coupled with finger changes. For example, a target on the left little finger during learning (palms downward) was again presented to the little finger at test (palms upward), although the little finger now occupied a different external location (see Design section below). Using these manipulations, transfer of learned tactile contextual cues was reliable in the anatomical skin based, but not the hand-centered external, condition. This pattern of results suggests that tactile contextual cues are represented in tactile contextual-cueing memory in terms of a finger-centered, anatomical reference frame.

Method

Participants

Sixty participants (2 x 30) took part in Experiments 1 and 2 (Expt. 1; 19 female, age range 19-35 years, 29 right-handed; Expt. 2; 23 female, age range 21-35 years, 30 right-handed). For both experiments, participants were randomly assigned to the two experimental groups, leading to 15 participants in each group (Expt. 1: anatomical vs. external group; Expt. 2: hand-centered-external vs. anatomical-skin-based group). All participants reported normal tactile perception and no history of somatosensory disorders. They received either course credit or 8 Euros/hour for their participation. Participants gave informed consent prior to the experiment, which was approved by the ethics committee of the Department of Psychology at LMU Munich, in accordance with the Code of Ethics of the

World Medical Association (Declaration of Helsinki). Because the current study aimed at investigating the reference frame(s) underlying tactile context cueing, it was necessary to select only participants who showed a reliable tactile contextual-cueing effect in the learning session (see, e.g., Zellin, Conci, Mühlenen, & Müller, 2013, for a similar procedure in visual contextual-cueing). Participants were identified as exhibiting successful context learning (in the learning session) when the slope of the function relating tactile contextual-cueing (i.e., the difference in reaction times between repeated and non-repeated configurations) to block number was positive. Another criterion to go on with the test session was an error rate ≤ 20% in the learning session. Only participants meeting both criteria went on to perform the final test session. Fifteen out of 75 participants were excluded.

Apparatus and Stimuli

The 8 vibro-tactile stimulations were delivered to the 4 fingers of each hand (thumbs excluded) through 8 solenoid actuators with a maximum finger contact area of 2-4 mm. Stimulus frequency was held constant at 150 Hz. The actuators activated lodged metal tips following the magnetization of the solenoid coils, controlled by a 10-Channel Tactor Amplifier (Dancer Design) connected to a National Instrument computer with a NI PXI-6723 analog output card. The experiment was controlled by a purpose-written Matlab program in combination with the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). Responses were recorded using foot pedals (Heijo Research Electronics, UK). Target-pedal assignment was counterbalanced across participants: half of them used the left (right) foot pedal for target 1 (target 2), and vice versa for the other half. Note that there were two different targets (one per trial) defined by two distinct square wave modulations (see Fig. 9A). Participants practiced this discrimination task in a dedicated session with normal vision. In this session, a fixation cross was presented (in addition to the symbol “T1” or “T2”; see below) in order to ‘cue’ observers to the visual response feedback given at the end of a trial (words “correct” or “incorrect”). Visual stimuli (i.e., instructions) were presented on a white canvas in front of the participant via an Optoma projector (HD131Xe). The projector was mounted on the ceiling of the experimental booth behind the participants. Vision was not possible in the subsequent experimental (learning and test) sessions, during which participants were blindfolded. In addition, they wore headphones (Philips SHL4000, 30-mm speaker drive) playing white noise (1000 Hz, ~65 dBA) to mask the tactile vibrations which would otherwise have been hearable in the sound-insulated testing cabin.

Procedure

Participants sat on a chair and had the actuators secured to their fingertips with masking tape. Additionally, participants wore adjustable cylindrical grips across each palm. This ensured that wrists, fingers and actuators were slightly raised, preventing contact with any surface. Participants placed their hands on a folded towel on their legs, though using the grips to avoid any contact with the legs during the experiment, so that the vibro-tactile stimulation was not distorted due to any pressure imposed by surface contact (see Fig. 9B). The experiment consisted of practice, learning, and test session, which together lasted some 45-60 minutes.

The practice session comprised two parts: target identification and tactile search. In the ‘practice-identification task’, participants were presented with only one stimulus at a time (target 1 or target 2), which was delivered to any of the eight fingers in a random fashion. In the ‘practice-search task’, the target was presented at the location of one randomly selected finger in combination with seven distractors presented at the remaining seven fingers. Both practice sessions consisted of three blocks of 16 trials (3 x 16). Because it was relatively difficult to verbally describe the target features, the symbols “T1” or “T2” were shown on the canvas for the initial 16 trials of each practice part, to help participants learn the appropriate target-pedal associations. Stimulators vibrated until a response was executed or until a maximum display duration of 3000 milliseconds (ms) elapsed. Visual feedback was given for 1000 ms after the participant's response. By using this relatively short presentation times, emphasis was placed on response speed as well as accuracy. In addition, error and time-out trials were followed by an "error warning" beep (2500 Hz, ~85 dBA, 900 ms). Each practice session was terminated when a participant achieved at least 80% accuracy in its last two blocks for both crossed and uncrossed positions in Experiment 1, or both palm-up and palm-down positions in Experiment 2. In general, participants required no more than two rounds of practice for each part.

The practice session was followed by the learning session, which was intended for the acquisition of tactile contextual cues. In this session, only 4 out of 8 fingers were stimulated (two on each hand) at the time, enabling the generation of different – repeated versus non-repeated – spatial configurations. Participants were randomly assigned to one of two learning conditions (Expt. 1: external vs. anatomical; Expt. 2: hand-centered-external vs. anatomical-skin-based). The initial hand position (un/crossed hands in Expt. 1, palm up/palm down in Expt. 2) was determined randomly and kept constant throughout the learning session, apart from the intervals (after every second block) in which participants were allowed to briefly alternate hand position back and forth for relaxation (they then continued with the original hand position). Participant's stepped on any pedal to resume the experiment. Importantly, and unlike in the practice session, participants were blindfolded during the learning (and test) session to prevent them from looking at their fingers, which, with time, might have allowed them to build up a visual representation of repeated tactile arrangements. Participants were instructed to discriminate the target as fast and as accurately as possible, and respond with the appropriate foot pedal. The end of every second block was signalled via a double beep (2 x 200 ms, 1000 Hz, ~72 dBA; separated by an 800 ms silent interval). After the last block of learning (block 14), participants were asked to alternate hand position and continue the search task with the new hand position in the final test session (of two blocks = 16 trials). Recall that for Experiment 1, if a participant performed the learning session with crossed hands, then she/he had to uncross her/his hands in the test session. Likewise, if a participant started Experiment 2 with the hands out-stretched with palm facing downward, then she/he had to turn her/his palms facing upward in the test session. The learning session comprised 14 blocks of 8 trials each (block = 4 repeated configurations and 4 non-repeated configurations). The test session consisted of two blocks, comprising 16 trials (4 repeated configurations presented twice and 8 non-repeated configurations).

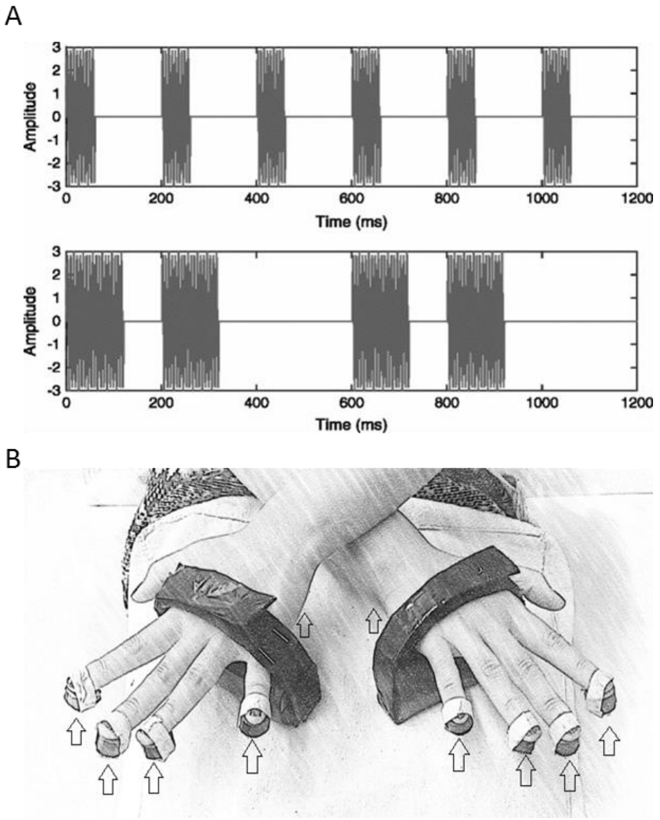

Figure 9. (A) Example of a postural (hand-crossed) manipulation with the hand grip used in the present study. In all conditions, the cylindrical grip insured actuators were slightly raised, preventing contact with any surface and thus distortions of the vibro-tactile stimulations. Upwards arrows point to gap between hand and leg surface. (B) The two targets at constant 150 Hz vibrations, defined by two distinct square wave modulations. Target 1 was defined by a 5-Hz square wave with a 30% duty cycle, and target two was defined by a burst square wave with an approximate frequency of 4.17 Hz with an average 30% duty cycle.

Design

Learning session

We adopted the tactile search paradigm used by Assumpção and colleagues (2015a). Each tactile search configuration consisted of four items (one target and three distractors), with two items being presented to each hand (see Fig. 10). Regarding the assignment of repeated and non-repeated configurations, for each participant a set of four repeated configurations was randomly generated at the beginning of the learning session, and repeatedly shown throughout the experiment. Conversely, non-repeated configurations were generated anew in each trial. It should be noted that throughout the learning session, target locations were held constant for repeated as well as for non-repeated configurations. This means that two fingers of each hand were reserved for repeated targets and the remaining four fingers (two from each hand) for non-repeated targets. Consequently, the target was equally likely to appear at any of the eight finger locations, preventing any bias to a particular finger. Further, since target location repetitions were equated across the repeated and non-repeated conditions, any reaction time benefit to the former can only be attributed to the effects of repeated context facilitation.

Test session

In the test session, participants were asked to change their hands to the alternative position. For Experiment 1, a change had to be made from crossed to uncrossed hands (or vice versa); for Experiment 2, participants were required to turn their hands (palms) from facing downward to upward direction (or the other way around). Following a change of hand position, a given configuration was presented in such a way that the items (target location in non-repeated configurations; target and distractor locations in repeated configurations) were either kept constant with regard to external or anatomical hand-based coordinates (Expt. 1), and, concerning the latter, configurations were kept constant with regard to hand-centered-external or skin-based coordinates (Expt. 2). Figure 2 illustrates how search configurations were remapped in each condition (group). Take the external group of Experiment 1 as an example: if in the learning session a target is projected at the external location occupied by the little finger of the left hand (uncrossed), in the test session this location is occupied by the index finger of the right hand (crossed). That is, the finger of the right hand overlapped with the previous finger of the left hand in external (but not anatomical) coordinates. By contrast, in the test session of the anatomical condition, the critical (target) item would still be presented to the little finger of the left hand. Specifically, anatomical (but not external) coordinates were kept constant across learning and test. By using these manipulations, it was possible to determine whether a learned tactile context continues to facilitate reaction time performance when it is presented at previous external or anatomical locations. The hypothesis of an external reference frame in tactile contextual-cueing (TCC) predicts an advantage for the external group, whereas the hypothesis of an anatomical reference frame predicts a benefit only for the anatomical group.

However, because search items are stable on fingers of the same hand in the anatomical condition of Experiment 1, this condition does not distinguish whether tactile contextual cues are learned relative to hand- or/and skin-based representations. This issue was addressed in Experiment 2, with two new – hand-centered external and anatomical-skin-based – conditions. In the hand-centered external condition, the original spatial layout of a given configuration was kept constant in external space relative to a given hand (but not fingers). For example, a target presented to the little finger of the left hand at learning (palm direction: downward) was presented at the same external location, now occupied by the index finger of the very same hand at test (palms facing upwards). Thus, following a turn of the hands at the transition from learning to test, the critical items were presented at the same external locations relative to a given hand. In the anatomical skin-based condition, the original spatial layout of a given repeated configuration was preserved for individual fingers across the learning and test sessions. For example, a target presented to the little finger of the left hand during learning was still presented to the same finger at test. Although with alternated palm direction the external coordinate changed, the skin-based reference frame was stable. On this note, if hand-centered, external coordinate mediates TCC, we expect a reliable transfer of the cueing effect in this condition. By contrast, the hypothesis of a skin-centered, anatomical reference frame of the cueing effect would predict a reaction time advantage only for the anatomical-skin group.

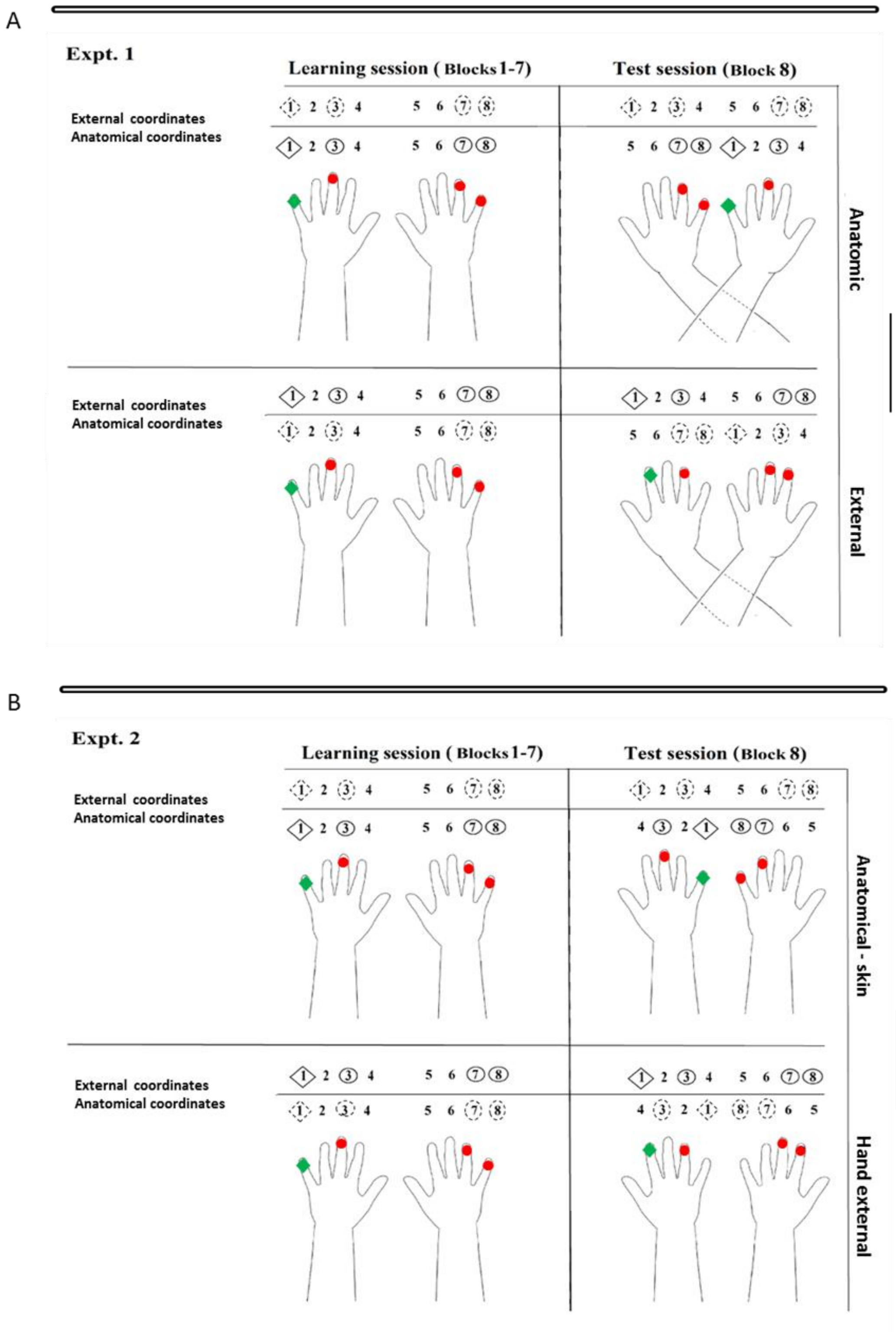

Figure 10. Spatial manipulations administered at the transition from the learning to the test session. (A) Expt. 1: un/crossing the hands. (B) Expt. 2: turning the hands. Diamond and circles represent vibro-tactile locations of target and distractors, respectively. Solid line shapes represent stable item locations across sessions in a given reference frame. Dashed line shapes represent compromised item locations across sessions in a given reference frame.

Results

Analysis of learning of tactile context cues

Experiments 1 and 2

Since the learning conditions were identical in Experiments 1 and 2, the build-up of tactile contextual-cueing was analysed by a single ANOVA. Error trials (see below) and trials with outlier reaction times (i.e., RTs exceeding 3 standard deviations above or below an individual's conditions means; <.1% of the trials) were excluded from reaction time analysis. In order to increase statistical power, we collapsed the data from every two experimental blocks, resulting in seven epochs in the learning session and one epoch in the test session. A dedicated mixed ANOVA on target effect on RTs with target (T1 and T2) as within subject and experiments as between subject factors failed to reveal any significant main effect or interaction, all p's >.321, as both targets were equally salient in all experimental conditions (T1: mRT = 1146 ms, SE = 30 ms; T2: mRT = 1154, SE = 28 ms). Performance accuracy and reaction times were then calculated for configurations and epochs for each participant and submitted to a 4-way, mixed-design ANOVA with the between-subject factors Experiment (1 vs. 2) and group (external vs. anatomical in Expt. 1; hand-centered external vs. anatomical-skin-based in Expt. 2), in addition to the within-subject factors configuration (repeated vs. non-repeated) and epoch (1-7). Data analysis was performed using R (R Core Team, 2016).

Error rates. The overall error rate in the learning sessions was 4.77%. No main effects or interaction were significant (all p's > .130), suggesting that performance accuracy was not systematically influenced by any experimental manipulation.

RT performance. The reaction time ANOVA revealed a significant main effect of configuration, F(1,56) = 111.07, p <.001 , $\eta_g^2 = .665$: participants were faster in identifying targets in repeated configurations (mRT = 1120 ms, SE = 28 ms) as compared to non-repeated configurations (mRT = 1178 ms, SE = 30 ms). The main effect of epoch was also significant F(6,336) = 21.17, p <.001, $\eta_g^2 = .274$: the reaction times became faster overall as the experiment progressed (epoch 1; mRT = 1256 ms, SE = 31 ms; epoch 7; mRT = 1089 ms, SE = 23 ms). Further, the configuration x epoch interaction was significant F(6,336) = 7.27, p <.001 , $\eta_g^2 = .115$: the reaction time advantage to repeated versus non-repeated configurations (cueing effect), was reliable from epoch 3 onwards (see Fig. 11 for the development of the cueing effect across epochs). No other effects were significant (all p's > .137). The overall lack of interactions, particularly those involving the factors experiment and group, suggests that learning of tactile contextual cues was comparable in the two experiments and groups.

Analysis of transfer of tactile context cues

Given that Experiments 1 and 2 differed with regard to the respective posture manipulations (external vs. anatomical in Expt. 1; hand-centered external vs. anatomical-skin-based in Expt. 2), transfer effects were examined separately for each experiment. Both analyses involved comparisons of reaction time performance between epoch 7 (the last epoch of the learning session) and epoch 8 (the sole epoch of the test session). Successful transfer of contextual-cueing would be indicated by an immediate reaction time advantage for repeated configurations in the test session. Individual mean RTs and response errors were entered in two separate (i.e., experiment-wise) 3-way mixed-design ANOVAs, each with group (external vs. anatomical in Expt. 1; hand-centered external vs. anatomical-skin-based in Expt. 2) as between subject factor and configuration (repeated, non-repeated) and epoch (7, 8) as within subjects factors. Error trials (see below) and outlier trials (<.1% in both Expt. 1 and 2) were excluded from RT analyses.

Experiment 1

In Experiment 1, participants performed the task with crossed (uncrossed) hands in the learning session and uncrossed (crossed) hands in the final test epoch. The main manipulation was that for one group of participants, item locations were kept constant across learning and test in terms of their external coordinates (external group). For the other (anatomical) group, item locations were maintained with respect to individual hands.

Error rates. The overall error rate was 2.97 %. None of the effects were significant (all p's >.134).

RT performance. The group (external, anatomical) x configuration (repeated, non-repeated) x epoch (7, 8) ANOVA revealed a significant main effect of configuration, F(1,28) = 13.05, p<.001, $\eta_g^2 = .318$: reaction times were faster to targets in repeated configurations (mRT = 1041 ms, SE = 29 ms) as compared to non-repeated configurations (mRT = 1108 ms, SE = 36 ms). The main effect of epoch was marginally significant, F(1,28) = 3,79, p = .06 , $\eta_g^2 = .119$: as reaction times tended to slow down in the test session (epoch 8: mRT= 1093 ms, SE = 33 ms) compared to the learning session (epoch 7: mRT= 1053 ms, SE = 32 ms). Further, the ANOVA revealed the configuration x epoch interaction to be significant, F(1,28) = 19,71, p < .001 , $\eta_g^2 = .413$, reflecting a marked reduction in tactile contextual-cueing from learning to test (epoch 7: TCC = 133 ms; t(29) = 7.39, p <.001, BF > 100; epoch 8: TCC < 0 ms; t(29) = .01, p = .989, BF = 5.143). However, as indicated by the significant three-way interaction, F(1,28) = 10.02 p = .004 , $\eta_g^2 = .264$, this pattern was attributable solely to the external group (epoch 7: TCC = 135 ms; t(14) = 5.4, p <.001, BF >100; epoch 8: TCC = -91 ms; t(14) = -2.35, p = .033, BF = 3.81). The anatomical group, by contrast, although there was a numerical TCC reduction of 38ms, the effect was significantly stable across sessions (epoch

7: TCC = 130 ms; t(14) = 5.03, p <.001, BF > 100; epoch 8: TCC = 92 ms; t(14) = 2.27, p =.039, BF = 1.84). No other effects were significant (all p's > .368).

Experiment 2

In Experiment 2, participants were randomly assigned to either the hand-centered-external or the anatomical-skin-based group. They had to learn the tactile configurations in a palm-down or palm-up position in the learning session; in the test session (epoch 8), they performed the task with the alternative hand position: palm up or palm down, while item positons were kept constant with regard to individual hands or fingers (hand-centered-external or the anatomical-skin-based group respectively).

Error rates. The overall error rate was 5.72%. The ANOVA revealed only the interaction between configuration and group to be significant F(1,28) = 4.25, p = .048, $\eta_g^2 = .131$. Follow-up t-tests showed that while participants in the anatomical-skin-based group were equally likely to err in repeated and non-repeated configurations (5.02% vs. 6.80%; t(29) = -.784, p = .439), the proportion of errors was higher in repeated compared to non-repeated configurations in the hand-centered-external group (5.50% vs. 2.10%; t(29) = 2.13, p = .041, BF = 1.38). Only 3 participants made response errors across both sessions, a t-test comparing the reaction times on these error trials failed to reveal a speed-accuracy trade-off, t(2) = -.483, p = .676, BF = 1.78).

RT performance. The ANOVA revealed a significant main effect of configuration, F(1,28) = 9.58, p =.004 , $\eta_g^2 = .255$: repeated configurations were responded to faster (mRT = 1096 ms, SE = 28 ms) than non-repeated configurations (mRT = 1179 ms, SE = 37 ms). The interaction between configuration and group approached significance F(1,28) = 3.53, p = .071, $\eta_g^2 = .112$, reflecting a numerically larger tactile cueing in the anatomical-skin-based than in the hand-centered-external group (TCC = 132 ms vs. 33 ms). Furthermore, the interaction between configuration and epoch was significant, F(1,28) = 4.39, p = .045, $\eta_g^2 = .136$, owing to a substantial reduction of the cueing effect from epoch 7 (TCC = 123 ms; t(29) = 4.22, p <.001, BF > 100) to epoch 8 (TCC = 40 ms; t (29) = 1.03, p = .309, BF = 3.17). Finally, and of theoretical importance, the three-way interaction between configuration, epoch, and group was significant, F(1,28) = 4.89, p = .035, $\eta_g^2 = .149$. Subsequent analyses showed that for the anatomical-skin-based group, cueing was near-equivalent between learning and test (epoch 7: TCC = 130 ms; t(14) = 2.65, p = .019, BF = 3.29; epoch 8: TCC = 134 ms; t(14) = 4.32, p < .001, BF = 52.23). This was in sharp contrast to the hand-centered-external group, where contextual-cueing was markedly reduced by the hand manipulation (epoch 7: TCC = 117 ms; t(14) = 3.46, p =.004, BF = 12.37; epoch 8: TCC = -52 ms; t(14) = -.808, p = .433, BF = 2.87). No other effects were significant (all p's > .163).

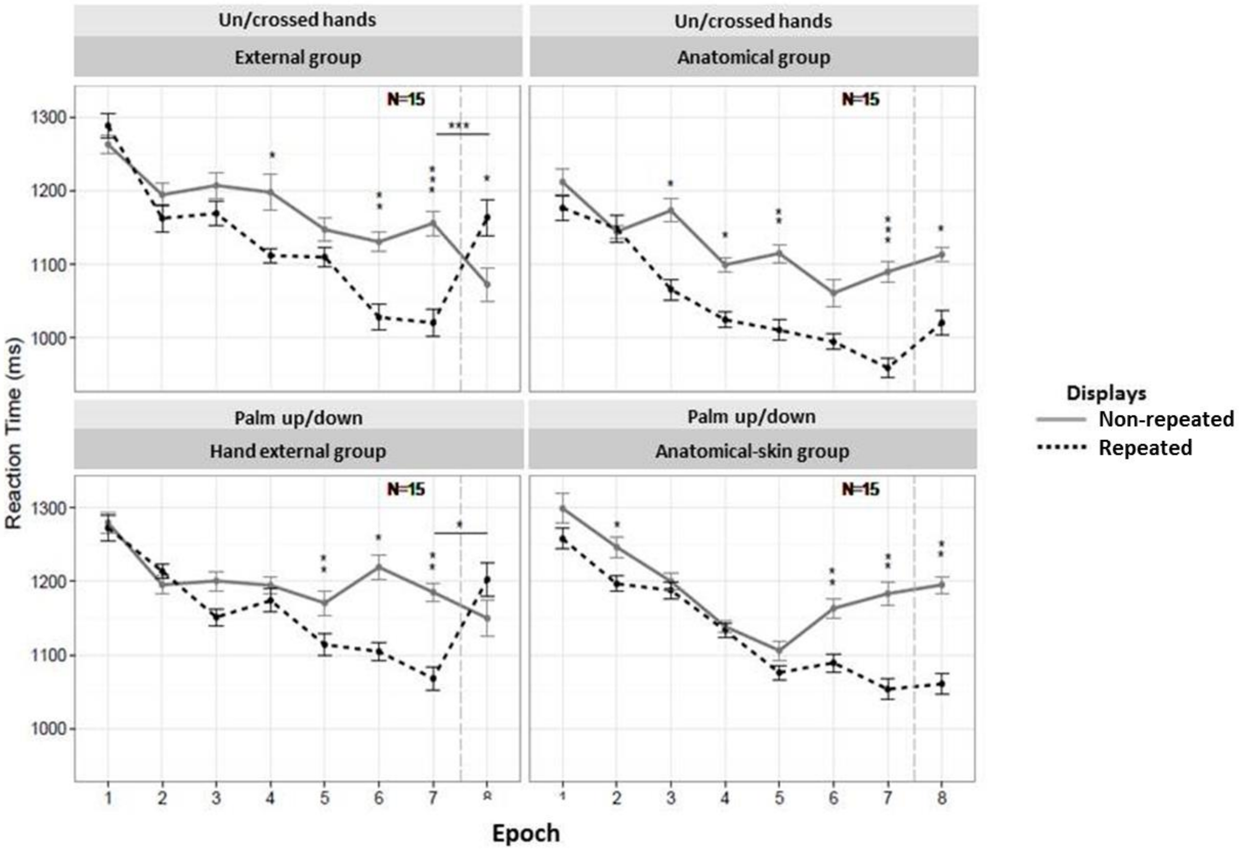

Figure 11. Reaction times to repeated and non-repeated configurations in the learning (epoch 1-7) and test session (epoch 8) for Experiment 1 (top panel; respective groups: external and anatomical) and Experiment 2 (bottom panel; respective groups: external-hand-centered, and anatomical-skin-centered). The error bars show ±1 standard error of the mean. Asterisks represent significance levels of p< .05 (*), p<.01 (**), and p< .001 (***). Reaction time differences between non-repeated and repeated displays in individual epoch were analysed using (two-tailed) t tests.

Discussion

Summary of findings

The present study investigated the reference frame(s) mediating the learning of spatial configurations in tactile search. More specifically, the experiments reported addressed two main questions: Experiment 1 posed the more general question as to an external versus an anatomical frame of reference underlying the tactile contextual-cueing effect. Experiment 2 shed more light on the precise nature of the anatomical representation by asking whether a hand-centered-external or a skin-based reference frame supported tactile context learning. Experiment 1 revealed that the memory representations underlying tactile context cueing is coded in an anatomical reference frame centered on the hand: after crossing (uncrossing) the hands, participants could take advantage of previously learned context cues only when these were presented at positions that were identical with respect to anatomical, rather than external coordinates. Experiment 2 corroborated with the previous experiment, by showing that learned tactile context was only reliable when presented to the same skin locations rather than to the same external-hand centered reference frame.

The current investigation is the first to explore and provide evidence regarding the spatial reference system underlying tactile context learning. Because one of the main ideas of the current study was to investigate purely tactile processing, participants were blindfolded and thus had no visual landmarks available to them to construct and use possible external references. Nevertheless, previously seen parts of the experimental chamber, such as the walls of the room, could have been used as genuine external landmarks. Further, other parts of the body (e.g., left vs. right leg, head, body midline, etc.) were available as potential sources for localization and could thus have provided additional reference frames. However, what is at odds with this proposal is that the transfer of learned contextual cues was highly selective and contingent on repetitions of the items’ exact hand and, in case of hand repetitions, successful transfer of contextual-cueing was observable only for repetitions of exact skin location. As mentioned in the Introduction, a possible explanation for the anatomical skin-based reference frame in tactile contextual-cueing might be that contextual-cueing in general supports spatial, that is, viewer-centered, navigation by helping to recognize viewpoint-dependent arrangements of items (scenes). An alternative idea is that of task-specific coding of references frames (Badde & Heed, 2016): given that the present tactile search task required observers to monitor their body (hands) this may have given an anatomical reference frame an extraordinary weight in spatial processing.

The co-existence of different spatial reference frames may also explain the somewhat unexpected result of tactile cueing, in the external group of Experiment 1, being significantly negative in the test session (TCC: - 91 ms, p = .033), that is, reaction times to repeated configurations were actually slower than reaction times to non-repeated configurations. If now assuming that in the current tactile search task, an anatomical reference frame is more appropriate than an external frame (Badde & Heed, 2016), this might also have entailed processes of active – effortful and time-consuming – deprioritization of the inappropriate – external – frame. Depriorization of the external frame may come to the fore particularly in the external group, because in this group there would be a 'strong' mismatch of the reference frames used for memorization of the repeated patterns (supported by an anatomical frame) and the encoding of the current stimulus array (supported by an external frame). Given this, RT disadvantages may reflect processes involved in the resolution of a conflict between different reference systems. An alternative, though not mutually exclusive, view would be to assume that the anatomical coordinate system of TCC is supported by different attentional mechanisms, namely: facilitation of target and inhibition of distractor locations (see, e.g., Ogawa, Takeda, & Kumada, 2007, for relevant evidence from visual contextual-cueing). If this idea is correct, reaction time disadvantages arise because the target, after hand position changes, may appear at the (anatomical) location of a previous, attentionally suppressed distractor item. Whatever, the explanation, both accounts assume a privileged status of anatomical representations in tactile contextual-cueing. Whether reaction time disadvantages result from a competition between multiple reference frames or whether negative cueing reflects carry-over of inhibitory spatial weights from previous distractor positions may be revealed by future studies.

Relation of TCC to other forms of statistical learning

Of note, the finding of anatomical TCC is consistent with other forms of statistical learning in the visual domain (besides viewpoint dependent representations in visual contextual-cueing; Chua & Chun, 2003), namely: probability cueing (Geng & Behrmann, 2005; Jiang et al., 2013). For example, in Jiang and colleagues (2013) targets were presented with a high probability in specific display quadrants, which led to reaction time advantages for these quadrants (relative to quadrants with low target probabilities). In a subsequent test session, participants changed their perspective by moving to a different position, while target probability was now equated across display quadrants. Interestingly, target detection was still faster for individual quadrants if they overlapped with the previous high-probability quadrant in terms of viewer-centered coordinates. Jiang and collaborators (2013) took this to mean that probability cueing is almost always coded in an viewpoint dependent reference frame, unless participants are explicitly told about the probability of target location (Jiang, Swallow, & Sun, 2014), or when target location probabilities are exceptionally uneven (Jiang et al., 2013; Experiment 4). These apparent similarities between probability cueing, visual contextual-cueing, and tactile contextual-cueing may suggest an abstract reference system that supports spatial learning in different – visual and tactile – modalities.

This issue is important in another respect, specifically; i) whether tactile context cues are merely stored in early cortical areas, where sensory representations are relatively short-lived and preserve the sensory input in raw form (TCC would thus be confined to individual stimuli /fingers). Or ii) if learned context cues are more permanently available and reside in higher brain areas, such as the medial temporal lobes, involved in modality-general statistical learning (e.g., Geyer, Baumgartner, Müller, & Pollmann, 2012; Preston & Gabrieli, 2008). Regarding the current study, the findings are in line with the former view (i), as TCC is bound to the fingers of the learning session. On the other hand, recent work in our lab showed that tactile context cues are functional at least 5 hours after the initial learning session (Assumpção et al. 2015b), which would make the long-term memory hypothesis of TCC more likely. This idea is further bolstered by the findings of Nabeta and colleagues. (2003), who showed a reliable transfer of contextual-cueing from the visual to the tactile domain, further highlighting the contribution of (long-term) modality-independent representations of the cueing effect. However, such transfer effects may also be due to the dominance of vision in spatial processing and the inference of abstract contextual-cueing memory would have required a fully orthogonal design. Given this, the interactions between different forms of contextual-cueing and their underlying (abstract) memory systems remain open.

Task-specific reference frame coding

Finally, the novelty and importance of the present findings does not only owe to the fact that to date little is known about tactile contextual-cueing; they also extend our general understanding of tactile perception. A great deal of knowledge regarding tactile reference frames comes from research using paradigms investigating relatively short-lived memory traces (e.g., Heed & Azañón, 2014; Medina, McCloskey, Coslett, & Rapp, 2014). While some of these studies show robust crossing effects - likely because of a conflict between the anatomical and external reference frames, this does not apply to the TCC task. That is, crossing of limbs (or flipping hands) does not affect tactile cueing (recall that the cueing effect was reliable in the anatomical condition of Expt. 1 and anatomical-skin-based condition of Expt. 2), suggesting that TCC is mainly supported by anatomical coordinates based on the skin. Of course, it is imperative to highlight that the current TCC task and previous investigations of tactile reference frames differ with respect to the required cognitive operations: fast and accurate support of the most apt effector to achieve a certain action goal (i.e., TOJ task) versus rapid recognition of the target in a previously learned search configuration (TCC task). Further, the present study was not designed to directly compare these tasks, but rather to add new knowledge as to the processes involved in tactile perception (contextual-cueing). In this regard, on the basis of the current findings, one may put forward the proposal that tactile processing, especially spatial coding, is highly sensitive to the nature of the task, likely reflecting differential requirements for tactile attention as a function of task demands.

Conclusion

To conclude, the present study investigated spatial coding in tactile contextual-cueing, a new form of statistical learning. It was found that TCC is supported by an anatomical, finger-centered reference frame. These findings add to the current literature on spatial representations in tactile perception that has hitherto been almost exclusively studied in tasks requiring transient forms of memory rather than long-term memory. Assuming that the current tactile search task had a bodily focus, accompanied by an anatomical reference frame, whereas other tactile tasks that require observers, e.g., to execute a movement, recruit an external reference frames. It therefore appears that the reference frames of tactile perception are adaptive and sensitive to task demands.

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Study III: Crossmodal contextual-cueing

Transfer of contextual-cueing between tactile and visual search tasks

Summary

Study III investigated whether memory of repeated context is sufficiently abstract to support information processes across the sensory modalities of vision and touch. To this end, we asked the question whether contextual-cueing acquired with modality X would facilitate search in modality Y, and vice versa. To date a bulk of studies has shown crossmodal facilitation in object recognition tasks. As an instance, objects pre-exposed in the haptic (visual) modality were recognized faster when tested in the visual (haptic) modality, as compared to non-exposed objects (Easton, Greene, & Srinivas, 1997; Reales & Ballesteros, 1999). Because investigations of implicit tactile learning and memory have been virtually ignored, very little knowledge concerning the transfer of information from a haptic task is available. A study by Nabeta, Ono, and Kawahara (2003) examined the commonality of implicitly learned spatial representations between vision and touch. By employing the 'classical' contextual-cueing task, consisting of repeated and non-repeated (baseline) displays, Nabeta and colleagues (2003) first reported a reliable contextual-cueing effect in the visual task. Subsequently, in a test session, participants sensed the repeated vs. baseline displays haptically. The results showed a robust contextual-cueing effect in the tactile task, suggesting that context memory acquired in the visual task can transfer to tactile search task contextual-cueing. Taken together, these findings from both studies accessing explicit and implicit learning showed that sensory modalities such as vision and haptic share considerable representational similarities, allowing for the interchange of information regarding object knowledge and spatial representations. Because Nabeta et al. (2003) only reported transfer of contextual facilitation from visual to tactile search, two important questions remained answered: (i) whether context learning occurs in the sense of touch (answered in Study I of this Thesis), and (ii) whether spatial regularities established particularly in the tactile search task transfer to a visual search task (and vice versa). The latter question is the focus of the current Study. In two experiments, participants learned spatial contexts either in a visual or tactile search task. In a test session, participants performed the search task through the alternative sensory modality. The results showed an asymmetrical transfer of contextual facilitation, especially: a robust transfer of the effect from the tactile to the visual search task, but not the other way around. It is suggested that although spatial maps are by default acquired in individual sensory modalities, there is also a crossmodal transfer of these memories, particularly when the information is learned through the most task-appropriate modality, which provides a knock-on benefit for spatial learning in the non-dominant modality. In this sense, the results of an asymmetric transfer of spatial memories in a multisensory search task support the crossmodal sensory calibration hypothesis (Gori et al., 2008; McGovern et al., 2016).

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Abstract

The contextual-cueing effect refers to a significant improvement in search performance when a target is repeatedly encountered in a stable set of distractors, as opposed to when it is part of a non-repeated distractor array. Given that the effect is well established in the visual domain, together with recent evidence of context effects in the tactile domain, the question arises whether contextual-cueing is supported by unimodal or supramodal spatial memory. We addressed this question in a fully orthogonal design by asking our observers to perform a tactile vs. visual search task in a learning session, which was followed by a visual vs. tactile search task in a transfer session. In the tactile task they had to discriminate a feature singleton target defined with regard to an amplitude difference relative to the distractor items. Targets and distractors were vibrating at a constant frequency of 150 Hz and delivered via stimulators attached to the fingertips of each hand. This task required scrutiny of temporal processing. In the visual task, the target was an orientation singleton (Gabor patch) and the visual items were presented at locations overlapping with observers' finger locations. Unbeknownst to them, half of the trials contained invariant target-distractor arrangements. These arrangements were preserved across the training and transfer session, while nevertheless a change of the type of (tactile, visual) search task was introduced at the transition of the two phases. A reliable contextual-cueing effect was found in both sensory modalities in the learning session. However, the transfer of cueing was asymmetric and observed only from the tactile to the visual search task. We interpret this finding as evidence for the supramodal representation view. But tactile and visual context learning could still be linked in the present search tasks by processes of crossmodal sensory calibration. Specifically, we suggest that the accuracy of a given sense for a given task dictates the direction of contextual-cueing transfer, such that learning-related gains in the temporal-accurate – tactile – modality benefit processing also in the other – visual – modality.

Introduction

Our sensory modalities effortlessly learn and use spatial regularities in the form of past experience to facilitate a quick scan of the sensory environment. One such mechanism for the efficient guidance of attention is contextual-cueing (Chun & Jiang, 1998). In their original experiments, Chun and Jiang's (1998) had participants perform a relatively difficult search for a target letter "T" embedded in a set of distractor letters "L". Unbeknownst to them, half of the trials contained repeated (sometimes referred to as 'old') displays, while the spatial arrangement of the target and the distractors was compiled anew in the other half of trials (referred to as non-repeated or 'new' displays). The standard finding is that search times are faster for repeated compared to non-repeated displays, an effect referred to as contextual-cueing. What is more, participants' ability to discriminate repeated from non-repeated displays is typically only at chance level. Chun and Jiang (1998) took these findings to mean that learned spatial target-distractor associations, stored in implicit long-term memory, come to guide the search, cueing attention to the target location.

Interestingly contextual-cueing is not limited to the visual modality (Assumpção, Shi, Zang, Müller, & Geyer, 2015, 2017). Using a new tactile search paradigm, Assumpção and colleagues demonstrated the contextual-cueing effect in a tactile search task. In their study observers were blindfolded and presented with white noise through headphones, so that tactile perception was prioritised. Magnetic vibrators were applied to four fingers of each hand (except the thumbs). On each trial, four fingers (1 target and 3 distractors) were stimulated simultaneously, two on the left and two on the right hand. All items vibrated at a constant frequency of 150 Hz. Observer's task was to discriminate between two possible targets, which were defined by an amplitude difference relative to the distractors (the latter defined by continuous sine waves). Like in the visual contextual-cueing paradigm, half of the trials contained repeated target-distractor arrangements; in the other half, the arrangements were non-repeated, (i.e., not encountered previously). The results revealed three key findings: (1) overall search times decreased as a function of time on the task (= effect of procedural or skill learning). (2) Search time improvement was greater for repeated than for non-repeated arrangements (= effect of context learning). (3) Observers ability to discriminate repeated from non-repeated arrangements was at chance level (= implicit context memory). Assumpção and colleagues (2015) took this set of findings to mean that the tactile modality has the capability for (implicit) configural learning, which facilitates tactile search.

Having established the contextual-cueing effect in the tactile modality, in the present study we examine the basic properties of the spatial memory that underlies the cueing effect, pursuing an approach that combines a tactile with a visual search task. Following tactile search and the development of contextual-cueing during training, a visual search task was introduced in which the locations of the visual items co-located with the previous finger positions (the order of tasks was reversed for the other half of observers). Our specific question was whether contextual cues developed in one modality would transfer to the other modality, and if so, how this transfer is characterized; uni-directional (e.g., from vision to touch) or bi-directional? The latter finding could index the operation of a supramodal spatial representation supporting the contextual-cueing effect.

Contextual-cueing as essentially spatial learning mechanism?

Prior studies showed that (visual) contextual-cueing is independent from the surface features of the items. For instance, Geyer, Zehetleitner, and Müller (2010; see also Olson & Jiang, 2004; Expt. 4) investigated contextual-cueing in relatively simple ‘pop-out’ search tasks. The important finding was that of a reliable contextual-cueing effect despite variable (i.e., non-repeated) assignment of the target's dimensional identity (color vs. orientation) across trials. This may suggest that visual contextual-cueing is supported by genuine space-based representations that come to guide the search process at the stage of integrated (dimension-unspecific) attention priority signals (see e.g., Johnson, Woodman, Braun, & Luck, 2007, for a related view). However, it is worth noting that many other studies do not support an account of contextual-cueing as merely spatial learning mechanism. Jiang and Chun (2001; see also Geyer, Shi, & Müller, 2010) observed that repeated target-distractor arrangements are learned within individual (color) groups of items that contain the target element. The more general implication of these findings is that contextual-cueing is dependent on attention (both in terms of selectivity and processing resources deployed; for the latter see, e.g., Annac et al., 2013). Specifically, Jiang and Leung (2005; see also Annac et al., 2013) showed that attention is a requirement, particularly in the expression (i.e., retrieval) of contextual-cueing rather than the initial build-up (i.e., acquisition) of memory of repeated display arrangements. That is, while configural learning proceeds in an automatic, attention-independent fashion, the retrieval of learned display arrangements from context memory is an attention-dependent process. Although contextual-cueing effects have been investigated mainly in visual search tasks, the finding of attention-dependent contextual-cueing may be taken to suggest that the cueing effect is itself bound to the visual modality or more generally: the sensory modality within which the learning took place, because selective attention enhances the processing (i.e., retrieval) of stimuli defined in the relevant modality and / or suppresses the processing of stimuli in other, non-relevant modalities. Concerning the latter, Kawashima, Roland, and O'Sullivan, (1995) showed that encouraging observers to perform a somatosensory task led to significant performance disadvantages in a concurrent visual task (decrease in the cerebral blood flow in the visual cortex), clearly demonstrating a suppressive effect of selective attention in a multisensory task.

On this background, the findings of a tactile contextual-cueing effect (Assumpção et al., 2015, 2017) and visual contextual-cueing effect (e.g., Chun & Jiang, 1998) are not necessarily diagnostic to the issue as to whether tactile and visual cueing share the same spatial representation or are based on different spatial learning mechanism(s). This question becomes particularly important if one considers the differential functional roles of touch and vision. Tactile spatial processing is closely related to peripersonal space, i.e., the space immediately surrounding us (Rizzolatti, Scandolara, Matelli, & Gentilucci, 1981; Rizzolatti, Fadiga, Fogassi, & Gallese, 1997) whereas visual spatial representations cover extrapersonal space that usually cannot be reached without moving. Restated: it is an open question whether context learning transfers from one to the other sensory modality and if so, whether this transfer is symmetric or asymmetric. If a transfer is shown this would greatly expand our knowledge of the contextual-cueing effect and statistical learning in general.

As it stands, there is only one study that addressed the issue of supramodal spatial representations in a contextual-cueing task (Nabeta, Ono, & Kawahara, 2003). In this study, observers underwent a 'standard' visual contextual-cueing task that was followed by a haptic search task. Visual displays consisted of 12 search elements that were distributed across an (invisible) array of 12 x 8 possible locations. Repeated arrangements were shown in 50% of the trials. The haptic displays consisted of search items elevated on plastic sheets. The non-repeated displays were generated anew, and haptic repeated displays replicated the spatial arrangement of the previously repeated visual-search displays. Nabeta et al. found facilitation of reaction times for repeated relative to non-repeated haptic arrangements when the repeated (tactile) arrangements were learned in a preceding visual search task (the same arrangements were used in the visual and haptic tasks). However, it was not clear whether this haptic contextual-cueing effect was driven by haptic or visual representations. That is, it could not be ruled out that in the haptic task, participants may have continued to operate an essentially visual strategy (for an elaboration of this view see Assumpção et al., 2015). Furthermore, and even more important to the present context is that Nabeta et al. did not address the issue of whether contextual regularities acquired in a tactile search task transfer to a subsequent visual search task, rather than in one way or another 'transferred' from the visual to the tactile modality. Given this, it was not possible to decide whether learned contextual cues are shared between the modalities of vision and touch and if so, whether this transfer was symmetric, which would constitute possible evidence for the operation of a supramodal spatial memory underlying the contextual-cueing effect.

Rationale of the present study

In the present work we investigate the issue of the transfer of contextual-cueing across the modalities of vision and touch in a fully orthogonal design. Half of observers performed first the tactile search task followed by the visual task (Experiment 1: T-V condition) and the other half started with the visual task followed by the tactile task (Experiment 2: V-T condition). In both tasks, the total number of stimuli in a given trial was limited to 4 (1 target, 3 distractors) and they were presented at a total of 8 possible locations arranged in a horizontal row in front of the participants (two stimuli appeared on the left and two on the right hemifield). In the visual task, observers searched for a target-grating stimulus defined by an orientation difference relative to the distractor-grating stimuli. The visual target and distractors were presented via back projection on a white canvas in front of the participants. In the tactile task, participants were blindfolded, wore headphones and had the magnetic vibrators attached to all fingertips except the thumbs. The target was defined by square-waveform amplitude difference relative to the distractor vibrations (frequency was constant at 150 Hz for both targets and distractors). Importantly, in the tactile task participants positioned their hands (fingers) in a way that finger locations overlapped with those of the visual stimuli. Given these identical locations, we were able to examine the ‘full’ transfer of learned target-distractor arrangements between the two modalities of vision and touch.

Predictions

Contextual-cueing in the tactile and visual search task could in principle be supported by a common (supramodal) or separate (unimodal) memory representation(s). The key approach here is to compare transfer effects in a fully orthogonal design, with each modality serving as training and transfer modality, respectively. A symmetric transfer is often considered as evidence for the existence of a supramodal spatial representation (e.g., Avraamides, Loomis, Klatzky, & Golledge, 2004) that may support contextual-cueing in a visual and tactile search task. This supramodal representation is independent of the modality in which spatial target-distractor associations were learned. Further, this view assumes that the contribution of supramodal memory to (search) tasks is comparable between tasks performed in the training and non-training modality. In essence, the notion of supramodal memory would predict a symmetric transfer of learned spatial arrangements from a tactile to a visual task or the other way around. Alternatively, it is possible that particularly tactile input is re-coded in the visual modality, e.g., because of task requirements (Nabeta et al., 2003) or even more important: because of the importance of vision in spatial processing (refs see below). Assuming that the present search tasks require spatial processing, then the most appropriate modality for solving this task would be the visual modality. This could mean that independent of the sensory input (visual, tactile) the repeated arrays are processed by the visual modality and thus recoded (and eventually also stored) in visual memory. This ‘visual-dominance’ account of contextual-cueing memory would also predict that (the transfer of) contextual-cueing is of similar magnitude regardless of the modality within which contextual cues were established. But there is a third possibility for the transfer of contextual-cueing memory traces. Specifically, inter-sensory effects can also stem from crossmodal sensory calibration (Gori, Del Viva, Sandini, & Burr, 2008; see also McGovern, Astle, Clavin, & Newell, 2016), which is different from the guidance of contextual-cueing by a supramodal (or visual) representation. In crossmodal sensory calibration, each modality would build up its own spatial representation but depending on the current task circumstances, it would assist spatial learning also in the other modality. For instance, it is well established that the visual modality exerts a spatial bias on information processing in other modalities, because spatial judgements are the dominance of this (visual) modality (e.g., Shelton & McNamara, 2001). According to the sensory calibration hypothesis, such bias could provide a knock-on benefit (which is equivalent to transfer) for contextual-cueing in the tactile task. Thus, the hypothesis of ‘visual calibration’ in spatial contextual-cueing predicts an asymmetric transfer of learned contextual cues from the visual to the tactile task (but not the other way around). However, it is also possible that contextual-cueing transfers particularly from the tactile to the visual task. Although this may sound counterintuitive in the first instance, a main feature of the tactile task is that the finger stimulations are spread over time and thus the detection and subsequent discrimination of the target requires scrutiny in temporal processing. Assuming now that temporal decision processes are the province of the tactile modality (e.g., Fujisaki & Nishida, 2009), one can make the prediction of a transfer of contextual-cueing from the tactile to the visual search task.

Of course, both causal principles, of visual and haptic sensory calibration, are not mutually exclusive and it is quite possible that in a multisensory search task both types of calibration occur. If it is now assumed that sensory calibration is equivalent, i.e., the influence of the visual task on the tactile task is the same as the influence of the tactile on the visual task, then also a symmetric transfer of the cueing memory across the two task would be likely. Thus, in addition to the proposals of supramodal cueing memory and visually-dominant cueing memory, there would be a third account that could explain symmetric transfer effects in a multisensory search task. – The present study, which was genuinely designed as a behavioural experiment, cannot distinguish between these ideas (given that the transfer of the contextual-cueing memory turns out to be symmetric). Instead, the main goal of the study is to clarify whether there is a transfer of context memory specifically from a tactile to a visual task (which is an essentially new question) and if so, how this transfer compares to a transfer from a visual to a tactile task (Nabeta et al., 2003).

Experiment

Method

Participants

Thirty six (2 x 18) healthy participants were randomly assigned to each experiment; Experiment 1, tactile learning followed by visual test (T-V) 12 females, 17 right-handed, mean age = 27.83, SD = 3.31, and Experiment 2, visual learning followed by tactile test (V-T) 9 females, 18 right-handed, mean age = 27.22, SD = 4.37. The experiment was approved by the ethics committee of the Department of Psychology at LMU Munich, in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). All observers agreed to participate in the study, for which they received either course credit or 8 Euro/hour for their participation. As both experiments aimed at a comparison of the transfer of the contextual-cueing effect from a learning to a test session, it was indispensable that a given participants exhibited a positive contextual-cueing effect in the learning session. For that reason, only observers with a positive contextual-cueing score in the training session were considered in the analysis. Such ‘positive’ observers were determined on the basis of the slopes of the function relating reactions times to experience on the task (i.e., epoch number) in the training session. Slopes were determined by means of a two-parameter power function of the form $RT = i*x^{s}$ (cf. Brooks, Rasmussen, & Hollingworth, 2010) applied to reaction times for repeated and non-repeated displays. Parameter i corresponds to the intercept of the RT x epoch function, and parameter s to the (negative) slope of the function; x represents the epochs (1-8). After determining the slopes for repeated and non-repeated displays, we calculated the difference in slopes between the two display types – providing a ‘pure’ measure of context learning (which is possible only with repeated displays) after removing contributions of procedural task learning (which applies to both repeated and non-repeated displays). Negative difference values indicate that the decrease in reaction times across epochs is larger for repeated than for non-repeated displays, indicative of ‘true’ context learning. Further, participants with error rates ≥ 30% in the learning session were excluded. This led to a total of 7 “excluded” observers out of the entire sample of 43 participants.

Apparatus and stimuli

The experiment was conducted in a dimly lit cabin. The visual stimuli were presented on a white canvas via an Optoma projector (HD131Xe). The canvas was fixed flat on a wooden frame, whose back was tilted about 20° towards the observer (see Fig. 12A). The viewing distance was fixed at about 60 cm. The visual stimuli consisted of four Gabor patches each subtending about 2.38° of visual angle presented on a grey background. The visual stimuli were presented on eight possible locations positioned along two invisible ‘curves’ over the horizontal axis (four locations in each curve). The invisible curves aimed at replicating the curvature formed by the locations assigned to each of the four tactors for each hand, so that visual stimuli were presented in spatially identical, horizontal plane. Inter-item distance was set at about 1.91° of visual angle. The frequency of each Gabor patch was set at 2 Hz. The orientation of distractors and targets were counterbalanced between participants. Furthermore, the tactile stimuli were formed by 8 solenoid actuators (each 2 - 4 cm maximum finger contact area), whose exact location could vary within ~3.5 cm in Y-direction and ~5.5 cm in X-direction (and ~6 cm space between the two hands) to best fit each participant’s fingers length. Each actuator contained a metal tip that vibrated when solenoid coils were magnetized. All items vibrated at a constant frequency of 150 Hz. The two possible targets (requiring left or right responses respectively) were defined by a square wave modulations (see Fig. 12B). Only one target was present in a given trial. The actuators were controlled by a 10-Channel Actuator Amplifier (Dancer Design) connected to a National Instrument computer with a NI PXI-6723 analog output card. A fixation cross cued participants to the center of the visual display at which during the tactile practice session a visual cue informed participants about the respective target identity (“T1” or “T2”). Note that observers could see the visual projection area in the practice session but were blindfolded in the tactile experimental session (see procedure section below). At the end of each trial, at the same screen location a response feedback was presented with the words “correct” or “wrong” for correct or wrong response. Response to tactile and visual stimuli was recorded via foot pedals (Heijo Research Electronics, UK). The assignment of pedal/target was counterbalanced between participants, in a way that half of the group had right (left) foot pedal responding to target T1 (T2) or the reverse for the other half of the group. In order to prevent participants from benefiting from aural cues produced by the actuators, headphones (Philips SHL4000, 30-mm speaker drive) playing white noise (1000 Hz, ~65 dBA) were used during the entire experiment. The experiment was controlled by a purpose-written Matlab program in combination with the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997).

Design and Procedure

The search tasks were preceded by written and verbal instructions given to each observer as well as familiarisation with the experimental devices. For example, chair height, foot pedals, and positions of the actuators (see Fig. 12A) were adjusted to enable participant's optimal comfort and performance. All parts of the experiment (instruction, familiarization, practice, learning and test sessions) lasted 60-80 minutes.

Practice

The practice session was divided into four parts. In all parts observers were asked to respond to the target identity (T1, T2) as fast and accurate as possible. Stimuli were presented for 3000 milliseconds (msec) or until a response was produced (whichever came first). The visual feedback was displayed 1000 msec after response. In addition to the visual feedback, incorrect and time-out trials were followed by an error-warning beep (2500 Hz, ~85 dBA, 900 msec) and an inter-trial interval of 2500-3000 msec. Each part of the practice (except *Practice 3*, see below) session consisted of 4 blocks (of 16 trials each). The end of every block was signalled by double beep (2 x 200 msec, 1000 Hz, ~72 dBA; separated by an 800 msec silent interval). Participants were allowed to take a short break and then resume the task by pushing any pedal.

Practice 1: tactile target identification. In the first part of the practice session, participants randomly experienced one of the two tactile targets at a time that could be stimulated at any one of the eight fingers. In this part of the experiment there were no distractors present and observers should 'just' learn the respective target identities associated response pedals. The first block always displayed the target ID "T1" or "T2" to help participants associate the target with its respective response pedal. This was done to compensate for the difficulties in verbally explaining target features. The target-pedal association learned in this practice part was kept constant across the entire experiment. In the subsequent three blocks (without displaying target identities) participants had to achieve at least 80% accuracy in order to enter the next part of the practice session. Otherwise participants were allowed to repeat this part.

Practice 2: tactile search. In the second practice part, each display consisted of one target and three distractors. Target (identity) and distractor locations were randomly selected for the eight fingers for each trial. Note that target-distractor patterns used in the practice part 2 were never used in the subsequent experimental. The aim of part 2 was to familiarize participants with the concurrent presentation of tactile search items (targets and distractors). In the end of the three practice blocks (3 x 16 trials) a visual feedback displayed accuracy rate, mean reaction time and standard deviation of the search performance. The last two values were noted by the experimenter to be used in the following adaptive visual search task. Again, participants had to achieve 80% task accuracy to proceed with the next practice part.

Practice 3: adaptive visual search task. In this part of the practice session participants trained the visual search, whose difficulty was controlled by changing the feature differences between visual target and distractors based on observers reaction time performance in the tactile task (from practice 2). We decided to use the performance in the tactile task as reference for the visual task since with the current version of the tactile task we were quite successful in demonstrating a tactile contextual-cueing effect (Assumpção et al., 2015; 2017. Visual search task difficulty was adjusted by the manipulation of orientation differences (ΔXº) of 5º, 7º, 9º, 11º and 16º between target- and distractor-Gabor patches. Each condition repeated 20 times, yielding a total 100 trials. Visual search parameters were defined as follows: 1) observer mean reaction times from the tactile task ($RT_{tactile}$) served as baseline for the visual search task. 2) The orientation of distractors (i.e., $X_dº$) were randomly selected between -6º to 6º (relative to the vertical line) at the beginning of the adaptive search task for each participant and then maintained throughout the experiment. The recorded RTs were fitted by an exponential function with ΔXº as factor ($RT=\Delta Xºe^{a}$; where a is the parameter fitted by the function), which then estimated the optimal orientation difference that could lead to minimum RT differences between the visual and tactile search task by the function $\Delta Xº = RT_{tactile} /e^{a}.5$). The final target orientation was defined by either $X_dº-\Delta Xº$ (target 1 that was rotated to the left compared to the distractors) or $X_dº+\Delta Xº$ (target 2 that was rotated to the right relative to the distractors. However, because the visual task was considerably easier compared to the tactile task, search performance could not be perfectly matched (see Results part). Participants were asked to respond to the direction of the target tilt relative to that of the distractor items. For example, when the tilt was left (right), the pressed the left (right) foot pedal. Target-pedal assignment was counterbalanced across participants.

Practice 4: visual and tactile search task. The relative difference of the angles of target and distractors revealed in the adaptive visual search task were entered in the program for the 'bimodal practice' part. The aim of this practice part was to compare ('double-check') search performance in the two sensory modalities, such as accuracy, RTs and standard deviations. At the end of each practice block, a feedback displayed these values for both visual and tactile trials. Based on this information participants were instructed to improve performance if accuracy was too low, or if RTs differed markedly between the two sensory modalities. At least three blocks of (16) search trials were administered in this part.

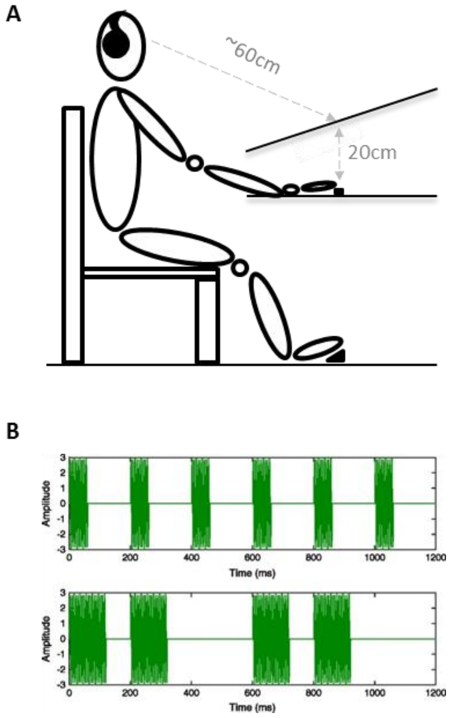

Figure 12 Experimental setup and features of tactile targets. (A) Graphic illustration of experimental set up. (B) Waveforms of two tactile targets. The upper panel indicates the waveform of Target 1 (T1), a 5-Hz square wave with a 30 % duty cycle delivered via 150-Hz vibrations. The lower panel shows the waveform of Target 2 (T2), a burst square wave (mean frequency of 4.17 Hz) with an average 30 % duty cycle delivered via 150-Hz vibrations.

Learning session

The tactile paradigm used in the current study is identical to the tactile search paradigm first used in Assumpção et al. (2015a, Expt. 3). Observers were blindfolded and wore headphones during the tactile task. Each search display consisted of four items (one target and three distractors per trial), with 2 items presented to each hand. For every participant an exclusive set of four repeated displays was generated at the beginning of the learning session thereafter each display repeated once per block. The non-repeated displays were always generated anew in every trial. In order to equate target location probability effect across repeated and non-repeated displays, two fingers of each hand were reserved for repeated targets and the remaining four fingers (two in each hand) reserved for non-repeated targets. Target locations were held constant across the entire experiment. Since targets were equally likely to be presented to each one of the eight locations, RT differences should be attributed to distractor-target associations rather than a bias to target location per se. The visual learning task was identical to the tactile learning, except that the visual stimuli were projected on the canvas placed about 20 cm above the actuator locations (see figure 12A). Observer's task was to search for a target and respond to its identity (tilt orientation) as fast and as accurate as possible. The learning session comprised 16 blocks of 8 trials each (4 repeated + 4 non-repeated displays). After every second block, a double beep signalled the end of the experimental block and participants could take a short break before reinitiating the experiment by stepping on one of the pedals.

Test session

At the end of the learning session, participants were allowed to take a short break whilst the test session was set by the experimenter. Subsequently, the participants again placed their hands on the table with their fingers on the actuators. The participants initiated the test session with a foot press, receiving either visual or tactile stimulation depending on the modality that was first used in the learning session. The locations of the target and distractor locations in repeated displays (and target locations in non-repeated displays) from the learning session were kept identical in the test session. For instance, if the tactile target and the three tactile distractors were delivered to the little finger (target) and middle finger (distractor 1) of the left hand and the indicator finger (distractor 2) and little finger (distractor 3) of the right hand in training, the visual items were projected at corresponding locations in the test session. Again, participants searched for the target and responded to its identity with focus on speed and accuracy. Note that the four non-repeated displays presented in the first block of the test session were also repeated in the subsequent blocks, so as to rule out a new 'session-driven'context learning between repeated and now novel displays. With this approach, any performance gains in the test session can only be attributed to the transfer of spatial memory from the previous learning session (for similar methods see Nabeta et al. 2003, Mednick, Makovski, Cai, & Jiang, 2009).

Results

In the following analyses, error trials and trials with extreme reaction times outside ±2.5 standard deviations (SD) of a given participant's mean reaction times were excluded from the RT analysis (< 1%). Additionally, and in order to increase the statistical power of our contextual-cueing effects (see Chun & Jiang, 1998), every two blocks of trials were collapsed into one epoch, thus resulting in 8 epochs in the learning session, and 4 epochs in the test session. Greenhouse-Geisser corrected p-values are reported in case sphericity was violated. Data analysis was performed using R (R Core Team, 2017).

Learning session

Errors

Error rates were relatively low in both experiments (Expt. 1: T-V = 3.69%; Expt. 2: V-T = 7.06%). For Experiment 1, a 2 x 8 repeated-measures ANOVA with the factors context type (repeated, non-repeated) and epoch (1-8) (only) revealed a significant effect of context type F(1,17) = 8.10, p = .011, η_p^2 = .332, all other p's > .202. Response errors were more frequent during search of non-repeated than repeated displays (4.84% vs. 2.56%). Further, and although the accuracy pattern mirrors that of reaction times (see below), we conducted a paired sample t-test on the error reaction times for repeated and non-repeated displays, which failed to reveal a speed accuracy trade-off effect: t(11)=.965, p = .177, BF = 1.91. For Experiment 2, the 2 x 8 repeated-measures ANOVA failed to reveal any significant main effect or interaction (all p's > .137).

Reaction Times

For Experiment 1 (T-V condition), a 2 (context type) x 8 (epoch) repeated-measures ANOVA revealed a main effect of epoch, F(7,119) = 4.98, p < .001, η_p^2 = .227, indicating an effect of procedural learning. RTs decreased as the experiment progressed (e.g., epoch 1; mean RT = 1160 msec, SE = .059; epoch 8; mean RT = 1031 msec, SE = .056). Further, RTs were significantly faster, by 42 msec, to repeated contexts (mean RT = 1035 msec, SE = .051 msec) compared to non-repeated contexts (mean RT = 1077 msec, SE = .055 msec), indexed by a reliable context type main effect, F(1,17) = 13.33, p = .002, η_p^2 = .440. The epoch x display type interaction was non-significant (p>.256). As shown in Figure 13 (left panel), this effect was due to the fact that contextual-cueing, expressed as the RT difference between repeated and non-repeated displays developed rather early in the tactile task.

For Experiment 2, an identical (2 x 8 repeated-measures) ANOVA revealed significant main effects of epoch, F(7,119) = 3.03, p < .028, η_p^2 = .152; RTs decreased with increasing numbers of epochs; epoch 1; mean RT = 901 msec, SE = .050 vs. epoch 8; mRT = 816, SE = .037. Again, responses to repeated contexts (mean RT = 826 msec) were significantly faster than responses to non-repeated contexts (mRT = 868 msec, SE = .039) indicating a significant contextual-cueing of 42 msec, F(1,17) = 4.48, p = .049, η_p^2 = .209. Similar to the T-V Experiment 1, in the V-T Experiment 2 contextual-cueing developed relatively rapidly in early epochs, indicated by the non-significant epoch x context type interaction (p > .443; see also Fig.13-left panel).

In sum, in both experiments, observers showed a general improvement of their search performance during the experiment (= effect of procedural learning). And yet, this improvement was greater for repeated compared to non-repeated displays (= contextual-cueing effect).

Test session

In this part of the analysis we focused on whether the context facilitation observed in the learning session successfully transferred to the alternative sensory modality in the test session. Recall that we repeated the spatial arrangements learned in the learning session. However, the four non-repeated displays initially shown in the first block of the transfer session were also repeated throughout this session to equate new learning of then repeated old' and 'novel' contexts in the transfer session. A successful transfer of contextual-cueing would thus be indicated by an extra gain in RT performance for old over novel (baseline) displays in the transfer modality.

Errors

Error rates were 6.54% and 8.43% for Expt.1: T-V and respectively Expt. 2: V-T. The 2 (display type) x 4 (epoch) repeated-measures ANOVA only revealed a significant main effect of epoch for Expt.1: T-V, F(3, 48) = 8.44, p = .001, η_p^2 = .115, as fewer response errors were made as the test session progressed (i.e., epoch 9 -12 = 12.97%, 5%, 2.64%, and 5.61 % respectively). All other p's > .231. For Expt. 2: V-T no effects were significant (all p's > .121).

Reaction Times

Separated 2 (display type) x 4 (epoch) repeated-measures ANOVAs were performed for Experiments 1 and 2. For Expt. 1: T-V, mean RTs decreased across individual epochs of the test session: main effect of epoch: F(7,51) = 3.09, p < .035, η_p^2 = .154 (epoch 9; mean RT = 929 msec, SE = .055 vs. epoch 12; mean RT = 849 msec, SE = .042). Further, there was a significant main effect of context type: F(1,17) = 13.01, p = .002, η_p^2 = .434. RTs were faster in old displays (mean RT = 828 msec, SE = .039) relative to novel displays (mean RT = 952 msec, SE = .059), suggesting a reliable contextual-cueing effect of 124 msec. In other words, contextual-cueing successfully transferred from a tactile to a visual search task. Importantly, the factor context type did not interact with epoch (p >.770), suggesting that contextual-cueing was reliable already in the first epoch of the test session (CC = 135 msec, t(17) = 3.08, p = .007, BF = 10.04) and thus successfully transferred from the tactile to the visual modality. For Expt. 2: V-T, on the contrary, the 2 x 4 ANOVA failed to reveal any significant main effects or interaction: all p's >.386. At least within four epochs, participants neither improved in their general performance, nor demonstrated a contextual-cueing effect. That is, no transfer of contextual memory acquired in the visual task to the subsequent tactile test, though contextual-cueing was highly reliable in the visual task.

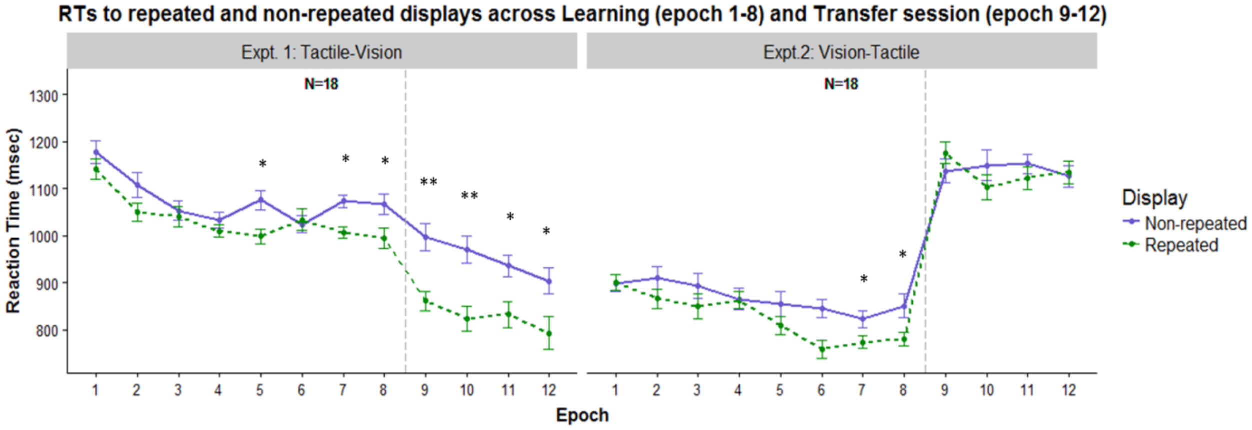

Figure 13. Reaction times to repeated and non-repeated configurations in the learning (epoch 1-8) and test sessions (epoch 9-12) for Experiment 1: T-V (left panel) and Experiment 2: V-T (right panel). The error bars show ±1 standard error of the mean. Asterisks represent significance levels of p< .05 (*), and p<.01 (**). Reaction time differences between repeated and non-repeated displays in individual blocks were analysed using (two-tailed) t tests.

Analysis of learning and transfer effects at the level of individual repeated displays

The non-finding of a transfer of contextual-cueing in Experiment 2: V-T condition may suggest that the cueing effect was overall low in the visual task and thus the transfer of memory from the visual to the tactile task was also low – and non-significant – in the V-T condition. However, what is at odds with this proposal is that initial contextual-cueing was fully comparable in magnitude in the V-T and T-V conditions (42-msec and 42-msec effects, respectively). However, mean RTs often vary substantially among observers, which makes it difficult to compare contextual-cueing scores across the training and test phases. For example, transfer effects (in the V-T condition) could result from a mixture distribution of observers showing a huge contextual-cueing effect initially but a reduced effect in the test accompanied by other observers that display a reliable contextual-cueing effect only later in the test phase (see, e.g., Zellin, Conci, Mühlenen, & Müller, 2013), for evidence pertaining to this claim at least from visual contextual-cueing). The single display analysis tracks, at the level of each observer, the status of a given repeated display across training and test. By this approach one can disentangle the transfer of contextual-cueing memory from late learning. For this reason, we further examined contextual-cueing effects across training and transfer at the level of individual repeated displays being able to check whether, e.g., a display that produced a contextual-cueing effect in the training session also showed a cuing effect in the test session. A repeated display was classified as generating contextual-cueing if RTs to this display fell under the 95% confidence interval (CI) of the participant's mean RTs for non-repeated displays (for similar approaches see, Colagiuri & Livesey, 2016; Geyer, Mueller, Assumpcao, & Gais, 2013; Smyth & Shanks, 2008). The 95-CI criterion was determined from both RTs to non-repeated displays in the learning and test session. We were thus able to parse individual repeated displays into four categories: (1) contextual-cueing display in training. This category represents repeated displays, in the training session, whose RTs were below the 95-CI criterion for non-repeated displays (determined in the training session). (2) Transferred displays. This category includes repeated displays that yielded fast RTs (< 95-CI) in both the training and test sessions. (3) Late learned displays are displays that did produce a cueing effect only in the later test session. Technically, RTs to these displays were above the 95-CI criterion in training but below this criterion in the test phase. (4) Non-cueing displays. This category represents displays that were above the 95-CI criterion in both the learning and test sessions. For the purpose of the single display analysis, we performed a 2 x 4 mixed-design ANOVA on the number of repeated displays, with experiment as between subject (Exp1. T-V vs. Expt.2 V-T), and display type (see above) as within subject factors. The ANOVA revealed a significant main effect of display type F(3,102)= 5.81, p< .005, η_p^2 = .146, however display type did not interact with experiment as p > .475. Further, there was a marginally significant effect of experiment F(1,34)= 3.12, p< .086, η_p^2 = .084. These results were further explored by independent t-tests, comparing the number of displays in each display category between the V-T Expt. 1 and the T-V Expt. 2. First, we notice a comparable number of contextual-cueing displays in the learning session between the two experiments (Exp. 1; M = 1.66, SE = .313 and Exp. 2; M = 1.83, SE = .232: t(34) = -.428, p = .672, BF = 2.893). This is an important result insofar as it supports (replicates) the equivalence of – mean – contextual-cueing in the tactile vs. visual learning phases (recall that both learning sessions produced identical CC effects of 42 msec). Next, we compared the number of contextual-cueing displays transferred to the test session, which was (numerically) greater in Exp. 1 (M = 1.11, SE = .254) than Exp. 2 (M = .55, SE = .184): t(34) = 1.76, p = .086, BF = 1.05. This result is also important because it provides some support for the asymmetric transfer of contextual-cueing across the test sessions. Furthermore, the number of late-learned displays observed in the two experiments was (numerically) again greater in Experiment 1 than Experiment 2: Exp. 1; M = .944, SE = .220; Exp. 2; M = .611, SE = .183; t(34) = 1.61, p = .254, BF = 1.14. The numerically higher number of late-cueing displays in Experiment 1 could explain why mean cueing was overall higher in the T-V condition in the subsequent transfer phase (Exp. 1; CC = 124 msec vs. Exp. 2; CC = 42 msec). Finally, the number of displays not learned was also comparable (Exp. 1; M = 1.38, SE = .303 and Exp. 2; M = 1.55, SE = .270): t(34) = -.409, p =.685, BF = 5.03.

Discussion

The present study investigated the contextual-cueing effect in a novel, visual-tactile search environment. Specifically, we tested whether repeated spatial context learned in one modality (e.g., touch) transferred to another modality (e.g., vision). In the T-V condition (Experiment 1), participants performed a tactile search task in the learning session and a visual search task in the test session. It was found that context-based facilitation of tactile search transferred to a later visual task. On the contrary, when participants first acquired context cues in a visual search task (V-T condition of Experiment 2), even though a reliable context effect was observed for the visual search task, presenting the tactile stimuli at the locations of the previous visual items did not lead to performance gains in the tactile task. A further single display analysis tracking the status of individual repeated displays across the learning and transfer sessions confirmed a greater transfer of contextual-cueing displays in the T-V compared to the V-T condition, even though initial visual vs. tactile cueing effects were comparable in terms of number of displays between the two conditions.

The present findings provide new insights into spatial learning and the accessibility of spatial information across sensory modalities. To the best of our knowledge the current study provides first evidence for the transfer of long-term contextual memory from the tactile to the visual modality, supporting the idea that there is a communication between somatotopic and visual representations (Nabeta et al. 2003). However, this interaction is not reciprocal, and appears to be mediated by mechanisms sensitive to the characteristics of the current task. One possible explanation for this finding is provided by the crossmodal calibration hypothesis (Gori et al., 2008; McGovern et al., 2016). This hypothesis posits that the sensory modality with the highest precision for a given task calibrates the other modality in that a surplus of performance due to learning in the 'dominant' modality is also expressed in the 'non-dominant' modality. Applied to the present investigation this could mean that the context-based facilitation of search in the tactile task – which requires scrutiny of temporal processing and is thus most appropriately supported by the tactile modality (Fujisaki & Nishida, 2009) – transfers to the visual task, reflected by a reliable context effect in this task. A further prediction of the crossmodal-sensory-calibration hypothesis is that while learning-related improvements of performance are in principle possible, in case of the involvement of the non-dominant modality in a given task, learning-related gains are confined to the this (non-dominant) modality. This idea receives support from the present V-T condition, which revealed a reliable contextual-cueing effect in a visual task in training but not in a tactile task when this task was performed in the subsequent transfer session.

Further, and given that the present tasks engaged spatial processing – with this series of actions being the territory of the visual modality (Shelton & McNamara, 2001) the crossmodal-sensory-calibration hypothesis would predict that cueing visually acquired would facilitate both visual and tactile search, whereas cueing acquired in the tactile task would confine to its own domain (as opposed to the present findings). This hypothesis could potentially explain the asymmetric transfer of contextual-cueing from the visual to the haptic modality observed by Nabeta et al. (2003). However, because the authors did not employ a fully factorial design (incorporating a tactile → visual, in addition to visual → tactile transfer session), other hypothesis need to be considered such as re-coding of the haptically sensed stimuli in a visual representation (Assumpção et al., 2015).

However, and with regard to the present finding of a non-transfer of cueing memory from the visual to the tactile task, it is possible that the spatial features of the visual task were inadequately low to trigger spatial processing. This means that the visual task may have been too easy, by means of the uniform (amorphous) spatial distribution of the search items in the horizontal display axis, in fostering an adequate spatial bias that is sufficiently strong to impact on information processing in the tactile modality. In this respect, note that the usual visual contextual-cueing task (e.g., Chun & Jiang, 1998) consists of display arrangements of 12 search items, 1 target and 11 distractors, which are widely distributed across both the horizontal and vertical display axes, thus forming 'true' spatial patterns. For this reason, and in attempt to thoroughly test the crossmodal-calibration-hypothesis, a future study could, e.g., employ a novel visual task in which the items are presented across both the horizontal and vertical display axes in an attempt to increase the requirements for space-based processing. The crossmodal calibration hypothesis would predict a transfer of contextual-cueing from the visual to the tactile task under these more visual-search like (2D) displays.

An alternative hypothesis would be that contextual-cueing is supported by a supramodal spatial memory or that training with the non-dominant modality may still recruit mechanisms (representations) of the dominant modality (e.g., Guttman, 2005). For instance, and assuming that spatial learning is dominated by the visual modality, it is possible that tactile contextual-cueing is effectively supported by the most task-appropriate visual representations, which would (a) predict a tactile contextual-cueing effect in the tactile training session and (b) a visual contextual-cueing effect in the visual test session. However, this idea would also suggest that visual representations acquired in the ‘visual’ training session should support tactile contextual-cueing in the ‘tactile’ test session. Yet this is not what we found. For this reason, and because we observed a reliable contextual-cueing effect in the tactile search task, it appears that the most parsimonious account of the present data is that of a relative dominance of the tactile over the visual modality in temporal processing (explaining a reliable cueing effect in the tactile task and a transfer of contextual-cueing from the tactile to the visual task), accompanied by a relative dominance of vision over touch in spatial processing. However, and because the current visual task may have been too easy in terms of space-based processing (though the ‘amorphous’ horizontal arrangements led to the build-up of a reliable contextual-cueing effect in the visual task), the effects of spatial bias (aka: crossmodal calibration) may have been too low under these (horizontal) presentation conditions. Thus, it is up to future research to test the transfer of contextual-cueing from a visual to a tactile task using more traditional visual search tasks (in which the items appear in a ‘true’ 2D layout). – Interestingly, under these more realistic visual search conditions it is well possible that contextual-cueing memories transfer across both tasks, leading also to symmetric transfer. Such symmetric transfer effects could then be the result of sensory calibration that is comparable in magnitude across the two tasks, such that the impact of sensory calibration resulting from the dominance of a given modality is identical for temporal vs. spatial processing. Under this view, tactile contextual cues acquired in the ‘temporal-dominant’ tactile modality would transfer to visual cueing and a contextual-cueing effect acquired in the ‘spatial-dominant’ visual modality would transfer to tactile contextual-cueing. Importantly, even if dominance effects are identical for the two tasks, this would not necessarily indicate the existence of a supramodal (or visual-dominant) contextual-cueing memory. Instead, symmetric transfer effects could also result from – separate – tactile and visual spatial memories that are nevertheless linked by the processes of sensory calibration. We leave this issue again up for future investigations.

Conclusion

In conclusion, the present findings show, for the first time, that context memory acquired in a tactile search task can facilitate visual search, but such crossmodal facilitation is not reciprocal. We take this finding to mean that the type of task can dictate the direction of the transfer of contextual-cueing facilitation. Linking this to the idea of crossmodal sensory calibration, it appears that the current tactile task efficiently engages temporal decision processes – which is the dominance of the tactile modality – and thus boosts subsequent information processing, i.e., a contextual-cueing effect, in a visual search task. By contrast, and although the visual task did itself exhibit context-specific facilitation of reaction times, crossmodal calibration – of spatial processing from the 'dominant' visual to the 'non-dominant' tactile task – may have been less pronounced in this task, perhaps because the spatial arrangements were too easy and / or to amorphous in this task. As a result, no transfer of learned contextual cues was observed from the visual to the tactile task. Overall, the results support the idea of separate, unimodal contextual-cueing memories for vision and touch, which are nevertheless linked by the process of crossmodal sensory calibration.

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Chapter IV: Deutsche Zusammenfassung

Der Gesichtssinn ist für die menschliche Orientierung und Informationsaufnahme das wichtigste Sinnesorgan. Mehr als 80% der Informationen über ihre Umwelt nehmen Menschen über den Sehvorgang wahr. Dies stellt hohe Anforderungen an die dem Sehen zugrundeliegenden Hirnstrukturen: obwohl das menschliche Gehirn über erstaunliche Verarbeitungsressourcen verfügt, ist seine Kapazität stark eingeschränkt. In der Folge sind Menschen nicht in der Lage, die Gesamtheit aller visuellen Informationen, zu einem gegebenen Zeitpunkt, bewusst wahrzunehmen. Daraus folgt, dass das visuelle System sich auf Ausschnitte der visuellen Welt einstellen muss. Auswahlprozesse spielen aber auch in anderen Sinnesmodalitäten – wie dem Gefühlssinn – eine wichtige Rolle oder wenn es darum geht, einen bestimmten Input mit (Langzeit-)Gedächtnisinhalten abzugleichen (was auch Prozesse des Lernens umfasst) bzw. einen Input zu einem Output (einer motorischen Reaktion) zu binden (was Prozesse der Ausführung von Mehrfachaufgaben oder Multitasking umfasst). Die neuro-kognitiven Mechanismen die solchen Auswahlprozessen zugrunde liegen werden als Aufmerksamkeit bezeichnet. Ein häufig eingesetztes Vorgehen zur Erforschung von Aufmerksamkeitsprozessen ist das *visuelle Suchparadigma*. In diesem Paradigma besteht die Aufgabe der Probanden i.d.R. darin, die Identität eines Zielreizes anzuzeigen, der zusammen mit Distraktoren dargeboten wird. Dabei werden Parameter wie die Gesamtanzahl der dargebotenen Reize (die sog. Displaygröße) oder die Ähnlichkeit des Zielreizes zu den Distraktoren (sog. Salienz) oder der Hintergrund in den die kritische Information eingebettet ist (sog. Kontext) variiert und als interessierende abhängige Variablen die Reaktionszeit (RZ) und der Fehleranteil (bzw. physiologische Parameter) bei der Ausführung der Suche erfasst. Aufbauend auf dem funktionalen Zusammenhang zwischen Displaygröße und RZ (bzw. Fehlern und / oder physiologischen Paramtern) kann auf die zugrundeliegenden attentionalen Verarbeitungsmechanismen geschlossen werden. Zahlreiche Arbeiten legen den Schluss nahe, dass die Auswahl kritischer Information von der Aufgabenart (einfache oder *Pop-Out-Suche* vs. schwere oder *Konjunktionssuche*), Stimulusfaktoren (Bottom-Up Faktoren wie bspw. Gruppierungsprozesse) und willentliche Faktoren (Top-Down Faktoren wie bspw. Instruktion, Vorerfahrung) gesteuert ist. Darüber hinaus ist die (visuelle) Suche nicht a-historisch: Stimuluseigenschaften aus vorangegangenen (Such-)Durchgängen entlang der gesamten Wahrnehmungs-, Kognitions- und Handlungsschleife haben einen modulierenden Einfluss auf die Suchperformanz im aktuellen Durchgang. Diese Gedächtniseinflüsse manifestieren sich auf unterschiedlichen zeitlichen Ebenen: von Millisekunden über Sekunden bis hin zu Minuten (Stunden) und werden als Priming- bzw. Kontexteffekte bezeichnet. Letztere lassen sich so verstehen, dass der Hintergrund – oder Kontext – die Suche nach der kritischen Information bahnt. Solche Zielreiz-Kontextverknüpfungen werden üblicherweise mit einem Langzeitgedächtnis in Beziehung gebracht, dessen Effekte nicht nur auf die (visuelle) Suche begrenzt ist, sondern auch zahlreiche andere kognitive Leistungsparameter beeinflusst. Beispiele sind Objekterkennung (einschließlich Wortererkennung), Gesichteridentifikation oder Szenenklassifikation. – Haben sich die bisherigen Untersuchungen nahezu ausschließlich auf die visuelle Suche kapriziert, verfolgt die vorliegende Promotion eine andere Stoßrichtung.

Im Zentrum der Arbeit steht die Untersuchung von Kontexteffekten in anderen Sinnesmodalitäten. Konkret wurde das Augenmerk auf die taktile Sinnesmodalität gelegt. Dieser Sinn umfasst verschiedene Qualitäten, wie Berührung, Druck, Vibration, weiterhin Temperatursinn und Schmerzempfinden. Taktile, taktil-kinästhetische und vestibuläre Sinnesinformationen sind eine wichtige Basis von (kognitiven) Erfahrungen. Die taktil-kinästhetische Sinnesmodalität hilft bei der Erkennung von Objekten und Orientierung im

Raum. Letzteres ließe sich auch so verstehen, dass die taktile Modalität in der Lage ist, ein eigenes (Kontext-)Gedächtnis zu etablieren, das die relative Lage des relevanten Reizes mit Bezug zu den Ablenker- oder Hintergrundreizen repräsentiert. Zur Untersuchung dieser Fragestellung wurde ein neues taktiles Suchparadigma konzipiert, in dem sich Prozesse der Bildung und des Abrufs – einschließlich des Transfers (in eine andere Sinnesmodalität) – des taktilen Kontextgedächtnisses untersuchen lassen. In diesem Paradigma wurden den Probanden Vibrationen mittels elektromagnetischer Sensoren an die Finger beider Hände (ausschließlich der Daumen) appliziert. In einem gegebenen Durchgang wurden jeweils zwei Finger der linken und rechten Hand stimuliert. Das Target war definiert durch eine relativ zu den (drei) Distraktoren abweichende Amplitude (realisiert mittels Amplituden-Wellenform-Manipulation); alle Reize wurden mit einer konstanten Frequenz (von 150 Hz) dargeboten. In einem gegebenen Durchgang sollten die Probanden zwischen zwei möglichen Targets diskriminieren und entsprechende Fuß-Tasten drücken. Die Suchperformanz (Reaktionszeit, Fehler) wurde in zwei experimentellen Bedingungen verglichen: alt und neu. Über diese Manipulation wurden die Probanden nicht informiert. In der alten Bedingung wurden sowohl Target als auch Distraktoren stets an identischen Fingerorten präsentiert (insgesamt gab es ein Set von vier alten Displays – in diesen Displays waren Target und Distraktoren an unterschiedlichen Fingerpositionen, die aber in Verlauf der Suche wiederholt stimuliert wurden). Die Performanz in der alten Bedingung mit der Suchleistung in einer neuen Bedingung verglichen. Hier wurde zwar die Position des Targetfingers, nicht aber die Positionen der Distraktorfinger über die einzelnen Durchgänge konstant gehalten. Folglich konnten nur in der alten, nicht aber neuen, Bedingung entsprechende Target-Kontextassoziationen gelernt werden. Während der taktilen Suchaufgabe waren die Probanden ‚blind' (sie trugen eine Schlafmaske) und ihnen wurde weißes Rauschen mittels

Kopfhörer eingespielt. Dadurch konnte eine Beteiligung der visuellen und akustischen Modalität an jedweden Kontextlernen in der taktilen Modalität minimiert (ausgeschlossen) werden. In Studie 1 wurde der zentralen Fragestellung nachgegangen, ob die taktile Modalität in der Lage ist, ein Kontextgedächtnis für die relative Position des Targets aufzubauen (die Antwort lautet: Ja). Studie 2 adressiert die Frage nach dem Koordinatensystem des taktilen Kontexteffektes. Theoretisch kann die relative Position des Targets mit Bezug auf anatomische oder externe (Umwelt-)Koordinaten im Kontextgedächtnis repräsentiert sein. Und hinsichtlich des anatomischen Referenzrahmens lassen sich diverse Koordinatensysteme differenzieren, wie ein hand- oder hautzentrierter Referenzrahmen (im Zusammenhang der vorliegenden Studie könnte ein hautzentrierter Referenzrahmen auch als fingerzentriertes Koordinatensystem bezeichnet werden). Die Frage des Referenzrahmens von taktilen Target-Kontextlernen wurde durch eine Manipulation der Hände (z.B. von gekreuzt nach ungekreuzt) beim Übergang von einer Lern- in eine Testphase angegangen. Dadurch konnten anatomische und externe Referenzrahmen selektiv manipuliert werden. Die Ergebnisse stützen die These, dass das taktile Kontextgedächtnis durch hautzentrierte Koordinaten vermittelt ist. In Studie 3 wurde das Lern-Testdesign wieder aufgegriffen. Allerdings wurde hier nicht die Handposition, sondern die Art der Suchaufgabe manipuliert. Konkret wurde Kontextlernen in einer taktilen und visuellen Suchaufgabe untersucht. Dazu wurden die Suchreize über Aufgaben hinweg an identischen Orten präsentiert, so dass bspw. die Fingerorte mit den Orten der visuellen Suchreize übereingestimmt haben (oder andersherum). In der visuellen Aufgabe wurden 4 Reize (1 Target, 3 Distraktoren) gezeigt und diese Aufgabe wurde hinsichtlich der Schwierigkeit mit der taktilen Aufgabe vergleichbar gemacht. Zum Einsatz kam ein voll-faktorielles Design, in dem jede Lernmodalität (visuell, taktil) mit jeder Testmodalität (taktil, visuell) kombiniert wurde. Die Ergebnisse zeigen einen asymmetrischen Transfer des Kontextgedächtnisses von der taktilen zur visuellen Modalität aber nicht andersherum, wobei in der visuellen Aufgabe selbst ein reliables Kontextgedächtnis nachgewiesen werden konnte. Dieses Befundmuster ist insofern bedeutsam, als das diverse Modelle des Zusammenspiels des räumlichen Lernens über Modalitäten hinweg ausgeschlossen werden können (wie eine supramodales oder visuelles Kontextgedächtnis). Vielmehr machen es die Befunde wahrscheinlich, dass crossmodale Effekte im Kontextlernen durch Prozesse der sensorischen Kalibrierung moduliert sind. Nach dieser These baut jede Modalität ihre eigenen Kontextrepräsentationen auf. Diese modalitätsspezifische Kontextlernen kann aber das Lernen in anderen Modalitäten beeinflussen, wobei dieser Einfluss adaptiv und von der Art der experimentellen Aufgabe abhängig ist.

Studie I

Eine umfangreiche Zahl von visuellen Studien hat überzeugend gezeigt, dass Menschen mühelos von statistischen Umweltregelmäßigkeiten (‚Kontexten') profitieren können, was wiederum die Suchleistung erleichtert, wenn der gelernte Kontext erneut abgesucht wird. Das Kontext-Cueing-Paradigma (Chun & Jiang, 1998) ist ein elegantes Messinstrument, um Prozesse des (räumlichen) Kontextlernen zu untersuchen. Wie aus den vorangegangenen Kapiteln ersichtlich werden sollte, zeigt sich im Kontext-Cueing-Paradigma häufig der Befund, dass die visuelle Suche innerhalb komplexer Zielreiz-Distraktoranordnungen im Laufe der Zeit schneller wird, da die im Langzeitgedächtnis gespeicherten Kontextrepräsentationen die Suche an den Ort der Zielposition bahnen können. Interessanterweise wird das Kontextgedächtnis als implizites Gedächtnis angesehen, da die Probanden, in einem dem Suchexperiment nachgelagerten Rekognitionstest, alte und neue Suchdisplays effektiv nicht unterscheiden können (wohl aber die alten Displays in der Suchaufgabe zu massiven Reaktionsvorteilen beitragen). –Die Dissoziation der Effekte des Kontextgedächtnisses auf die (implizite) Suchleistung und (explizite) Rekognitionsleistung wird üblicherweise als Hinweis auf ein implizites Kontextgedächtnis angesehen. Während das Studium von Kontext-Effekten größtenteils in der visuellen Modalität stattfindet, vernachlässigt die wissenschaftliche Gemeinschaft die Beiträge oder sogar die unabhängige Kapazität anderer sensorischer Modalitäten für das Kontextlernen. Es ist wahr, dass die Informationsverarbeitung durch den Sehsinn dominiert ist (s.o.). Dies schließt jedoch nicht aus, dass auch andere sensorische Modalitäten im räumlichen Lernen eine wichtige Rolle spielen. Eine in diesem Zusammenhang bedeutsame Frage ist, ob auch die taktile Modalität die Fähigkeit zum Kontextlernen besitzt. Studie 1 dieser Arbeit widmet sich dieser Fragestellung. Hier wurde ein experimentalpsychologisches Setup entworfen, das die wichtigsten Merkmale der visuellen Kontext-Cueing-Aufgabe inkorporiert. Konkret wurden den Probanden alte und neue taktile Konfigurationen gezeigt. Jede Konfiguration bestand aus vier Stimuli (ein Zielreiz mit drei Distraktoren), mit jeweils zwei Reizen an einer Hand. Alle Finger (außer die Daumen) wurden als mögliche Reizorte verwendet. Die Probanden berichteten entweder den Ort des Zielreizes (Experimente 1 und 2) oder dessen Identität (Experiment 3) indem sie ein entsprechendes Fußpedal so schnell und so genau wie möglich drückten. Ähnlich wie beim visuellen Kontexteffekt konnte auch in der taktilen Aufgabe eine Verbesserung der Suchleitung über die Zeit (=taktiler Kontexteffekt) nachgewiesen werden. Die Ergebnisse dieser Studie zeigten, dass auch die taktile Modalität ein eigenes Kontextgedächtnis bilden kann, wodurch die Zielreizentdeckung beschleunigt wird. Darüber hinaus zeigte eine nachgelagerte explizite Wiedererkennungsaufgabe (dargeboten in Experiment 3), dass die Versuchspersonen die alten taktilen Kontexte nicht von den neuen Kontexten unterscheiden konnten. Studie 1 zeigt also, dass die taktile Sinnesmodalität ein eigenes – implizites – räumliches Kontextgedächtnis ausbilden kann.

Studie II

Die zweite Studie dieser Arbeit betrifft den Referenzrahmen, der dem taktilen Kontextlernen zugrunde liegt. Referenzrahmen legen fest, an welchen Ort die Aufmerksamkeit gebahnt wird, wenn ein altes Display in nachfolgenden Suchdurchgängen verarbeitet wird. In der taktilen Modalität ist diese Frage nicht trivial, weil sich Effektoren (Gliedmaßen) innerhalb eines bestimmten Raumes nur in der Nähe des Körpers bewegen können und in einigen Fällen sogar einen Konflikt verursachen, wenn bspw. ein taktiler Reiz an der rechten Hand erscheint (= anatomischer Bezugsrahmen), wobei beide Hände überkreuzt sein können und die rechte Hand damit auf der linken Raumseite (=externer Referenzrahmen) erscheint. Wurden taktile Referenzrahmen bisher in verschiedenen Paradigmen untersucht, wie der zeitlichen Reihenfolgeaufgabe (Badde & Heed, 2016), ist es eine offene Frage, ob eine Verschiebung der Aufmerksamkeit zur gelernten Zielreizposition in einer taktilen Anordnung von einem anatomischen oder externen Referenzrahmen unterstützt wird. Im Gegensatz zur zeitlichen Reihenfolgeaufgabe, in der die Probanden eine Reihenfolge-Entscheidung hinsichtlich des Eintreffens von zwei unmittelbar hintereinander präsentierten Reizen an z.B. der linken und rechten Hand treffen sollen (folglich erfordert diese Aufgabe nur eine transiente Speicherung der beiden Reize), ist das Kontextgedächtnis in der taktilen Suchaufgabe relativ langlebig und wird durch andere Formen des (Langzeit-)Gedächtnisses unterstützt. In Studie 2 dieser Arbeit wurde die taktile Aufgabe in eine Lern- und Testsitzung geteilt. Diese Teilung erfolgte mit zwei Zielsetzungen: Erstens, um zu untersuchen, ob das Kontextgedächtnis im Allgemeinen von einem anatomischen oder externen Referenzrahmen gestützt wird. Dazu haben die Probanden die taktilen

Anordnungen ihre Gliedmaßen beim Übergang von der Lern- in die Testsitzung gekreuzt bzw. wieder „entkreuzt" (Experiment 1). In der anatomischen Bedingung wurden die Zielreiz- und Distraktorpositionen aus der Lernsitzung so präsentiert, dass die Finger, die den Zielreiz und die Distraktoren enthielten, in beiden Sitzungen identisch waren. In der externen Bedingung wurden dagegen die externen Raumkoordinaten von Zielreiz und Distraktoren in gelernten Anordnungen über die Sitzungen konstant gehalten. Die Ergebnisse zeigten, dass das taktile Kontextgedächtnis in einem anatomischen Referenzrahmen kodiert wird. Aufbauend auf diesem Befund wurde zweitens der anatomische Referenzrahmen des taktilen Kontextgedächtnisses weiter untersucht (Experiment 2). Konkret wurde ein handzentriertes versus hautzentriertes Referenzsystem des taktilen Kontextgedächtnisses untersucht. Dazu führten die Teilnehmer die taktile Suchaufgabe in der Lernsitzung mit in einer parallelen Position ausgestreckten Händen durch. In der nachfolgenden Testsitzung sollten die Probanden die Hände nach oben (oder unten), also um um 180˚, drehen (50% der Probanden haben Experiment 2 mit nach oben und 50% mit nach unten gerichteten Händen begonnen). In der hautzentrierten Bedingung wurden die Konfigurationen an denselben Fingern über beide Sitzungen präsentiert, während in der handzentrierten Bedingung Zielreiz und Distraktoren in gelernten Anordnungen an denselben äußeren Koordinaten mit Bezug auf eine gegebene Hand gargeboten wurden. Die Ergebnisse zeigten einen „Übertrag" des Kontextgedächtnisses von der Lern- in die Testsitzung in der hautzentrierten, nicht aber handzentrierten, Bedingung. Folglich kann mit hoher Wahrscheinlichkeit davon ausgegangen werden, dass taktiles Kontextlernen durch ein anatomisch-hautzentrierten Referenzsystem unterstützt ist. Diese Erkenntnisse ergänzen die gegenwärtige Literatur über räumliche Referenzrahmen in der taktilen Wahrnehmung, die bisher ausschließlich in Aufgaben untersucht wurde, die Kurzzeitgedächtnisprozesse erfordern (und nicht

Langzeitgedächtnisprozesse, wie in der aktuellen Aufgabe). Unter der Annahme, dass in der taktilen Suchaufgabe die Probanden ihren Körper „überwachen“ müssen – also eine Entscheidung treffen müssen, an welchem Finger das Target präsentiert präsentiert wurde (und wie es definiert ist), könnte dies zu einem anatomischen Bezugsrahmen geführt haben. Auf der anderen Seite wurde auch die Existenz von externen Referenzrahmen in taktilen Aufgaben berichtet und zwar dann, wenn die Beobachter eine Bewegung im Zuge der Lokalisation des taktilen Targets ausführen sollten. Es scheint also so zu sein, dass die Bezugsrahmen für taktilen Wahrnehmung – einschließlich Gedächtnisbildung – adaptiv und empfindlich für die Aufgabenanforderungen sind.

Studie III

Studie 3 untersucht die Fragestellung, ob gelernte Kontexte genügend abstrakt sind, um Informationsprozesse über die sensorischen Modalitäten des Sehens und der Berührung zu unterstützen. Konkret wurde untersucht, ob ein Kontextgedächtnis das in der Modalität X erworben wurde, auch Suchprozesse in der alternativen Modalität Y erleichtern würde (und umgekehrt). Bisher hat ein Großteil solcher – crossmodaler – Studien eine übergreifende Erleichterung in Objekterkennungsaufgaben gezeigt. Beispiel: Objekte die in der haptischen (visuellen) Modalität vorexploriert wurden wurden schneller erkannt, wenn sie in der alternativen visuellen (haptischen) Modalität getestet wurden, im Vergleich zu Objekten, die nicht vorexploriert waren (Easton, Greene, & Srinivas, 1997; Reales & Ballesteros, 1999). Da allerdings Untersuchungen zum impliziten taktilen Gedächtnis praktisch nicht existent sind, ist sehr wenig Wissen über die Übertragung von Informationen aus einer haptischen in eine visuelle Aufgabe verfügbar. Eine Studie von Nabeta, Ono, and & Kawahara (2003) untersuchte den Transfer implizit gelernter räumlicher Anordnungen zumindest von einer visuellen zu einer taktilen Suchaufgabe unter Einsatz der "klassischen" Kontext-Cueing-

Aufgabe, bestehend aus alten und neuen (visuellen) Displays. Nabeta und Kollegen (2003) konnten zunächst einen zuverlässigen Kontext-Effekt in der visuellen Aufgabe zeigen. Anschließend haben die Teilnehmer die gelernten (und neue) Displays in einer Test-Session haptisch exploriert. Die Ergebnisse zeigten einen robusten Kontext-Effekt in der taktilen Aufgabe, was darauf hindeutet, dass der in der visuellen Aufgabe erworbene „Kontextspeicher" auf die taktile Suchaufgabe übertragen werden kann. Da aber Nabeta et al. (2003) nur die Übertragung der kontextuellen Erleichterung von der visuellen zur taktilen Suchaufgabe untersucht haben, wurden zwei wichtige Fragen beantwortet: (1) ob das Kontextgedächtnis auch in der taktilen Modalität erworben werden können (beantwortet in Studie 1 dieser Promotionsarbeit) und (2), ob das taktile Kontextgedächtnis auch auf eine visuelle Suchaufgabe übertragen werden kann. Die letztere Frage steht im Mittelpunkt von Studie 3 der Arbeit. In zwei Experimenten lernten die Teilnehmer räumliche Kontexte entweder in einer visuellen oder taktilen Suchaufgabe. In einer anschließenden Testsitzung führten die Teilnehmer die Suchaufgabe in der alternative sensorische Modalität durch. Beide Aufgaben waren hinsichtlich der Schwierigkeit (gemessen mittels Reaktionszeit in einer Übungssitzung) vergleichbar und beim Übergang von der Lern- zur Testphase wurden die Suchreize an räumlich identischen Orten präsentiert. Die Ergebnisse zeigten eine asymmetrische Übertragung der kontextuellen Erleichterung, konkret: eine robuste Übertragung der Wirkung von der taktilen auf die visuelle Suchaufgabe, aber nicht von der visuellen zur taktilen Aufgaben – obwohl in der visuellen Suchaufgabe selbst ein reliabler Kontexteffekt nachgewiesen wurde. Auf der Basis dieses Befundmusters wird vorgeschlagen, dass räumliche Karten standardmäßig in individuellen sensorischen Modalitäten erworben werden, dass aber ein Lernen in anderen, alternativen Modalitäten angestoßen werden kann, insbesondere wenn die Kontextrepräsentationen in der Modalitäten erworben werden, die die entsprechende experimentelle Aufgabe optimal unterstützen. In diesem Sinne stützen die Ergebnisse einer asymmetrischen Übertragung von räumlichen Kontexterinnerungen in einer multisensorischen Suchaufgabe die crossmodale sensorische Kalibrierungshypothese (Gori, Del Viva, Sandini, & Burr, 2008; McGovern, Astle, Clavin, & Newell, 2016).

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Appendix

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Contextual cueing: implicit memory of tactile context facilitates tactile search

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Abstract In visual search, participants detect and subsequently discriminate targets more rapidly when these are embedded in repeatedly encountered distractor arrangements, an effect termed *contextual cueing* (Chun & Jiang *Cognitive Psychology, 36*, 28–71, 1998). However, whereas previous studies had explored contextual cueing exclusively in *visual search*, in the present study we examined the effect in *tactile search* using a novel tactile search paradigm. Participants were equipped with vibrotactile stimulators attached to four fingers on each hand. A given search array consisted of four stimuli (i.e., two items presented to each hand), with the target being an odd-one-out feature singleton that differed in frequency (Exps. 1 and 2) or waveform (Exp. 3) from the distractor elements. Participants performed a localization (Exps. 1 and 2) or discrimination (Exp. 3) task, delivering their responses via foot pedals. In all three experiments, reaction times were faster when the arrangement of distractor fingers predicted the target finger. Furthermore, participants were unable to explicitly discriminate repeated from nonrepeated tactile configurations (Exps. 2 and 3). This indicates that the tactile modality can mediate the formation of configural representations and use these representations to guide tactile search.

Keywords Contextual cueing · Implicit memory · Attention · Tactile search · Haptics · Touch

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Humans experience a myriad of events at any given time, presenting an excessive load of information to the brain. However, most events or objects do not occur in isolation; rather, they are embedded in larger, structured environments. Previous work has shown that environmental regularities are permanently retained and facilitate visual perception. For instance, in a seminal study by Palmer (1975; see also Biederman, 1972; Biederman, Mezzanotte, & Rabinowitz, 1982; Chun, 2000; Hollingworth, 1998), participants were presented with a scene context (e.g., a kitchen counter) followed by a brief presentation of a target that was either context-appropriate (e.g., a loaf of bread), context-inappropriate but similar in shape to the appropriate object (e.g., a mailbox), or completely context-inappropriate (e.g., a drum). In a subsequent naming task, participants showed higher performance accuracy in the context-appropriate than in the two context-inappropriate conditions. Palmer concluded that *visual object recognition* is modulated by scene context.

The beneficial effect of environmental information on *visual selective attention* was further elucidated by Chun and Jiang (1998), by means of their contextual-cueing paradigm. In this task, participants have to detect and subsequently discriminate the orientation (left vs. right) of a target "T" embedded in a set of distractor "L"s. Unbeknownst to participants, half of the trials contain repeated and the other half nonrepeated target–distractor spatial arrangements. In the repeated—*old*—condition, both the target and the distractors are presented at identical display locations across trials. By contrast, in the nonrepeated—*new*—condition, only the targets (but not the distractors) appear at identical locations (by keeping target locations constant in the old and new displays, one can equate target location repetition effects between the two types of displays and thus isolate the effect of context on reaction time—RT—performance). Chun and Jiang found that participants were faster at detecting the target in old than in new displays, an effect referred to as *contextual cueing.*

Interestingly, when participants were asked to discriminate the repeated from the nonrepeated displays, explicit recognition was only at chance level. This dissociation in direct (recognition) and indirect (RT) measures led Chun and Jiang to surmise that contextual cueing is supported by an implicit memory system.

In recent years, Chun and Jiang's (1998) basic findings and paradigm have inspired numerous studies. For example, van Asselen and Castelo-Branco (2009) showed that contextual cueing was still obtained in a test session when the training and test sessions were separated by 10 days. Geyer, Müller, Assumpção, and Gais (2013) found that even a short nap relative to an equivalent period of controlled rest separating the learning and test sessions (on the same day) was sufficient to enhance contextual cueing. Other investigations have demonstrated that, rather than relying on the entire distractor context, contextual cueing is supported by memory for individual target–distractor (paired) associations formed particularly in the vicinity of the target (Brady & Chun, 2007; Jiang & Wagner, 2004; Shi, Zang, Jia, Geyer, & Müller, 2013), or amongst distractors sharing the target's color (Conci, Müller, & von Mühlenen, 2013; Geyer, Shi, & Müller, 2010). Additional work has shown that contextual learning (i.e., the acquisition of contextual memory) and expression (i.e., the retrieval of contextual memory) are separate processes (Chaumon, Schwartz, & Tallon-Baudry, 2009) and that an additional (spatial working memory) task interferes with the retrieval, but not the learning, of contextual memory representations (Annac et al., 2013).

Taken together, the by now extensive body of studies on contextual cueing in *visual* search has contributed substantially to our understanding of the processes underlying *implicit spatial learning*. Although sensory modalities other than vision have received considerable interest in recent years (e.g., Klatzky, Lippa, Loomis, & Golledge, 2002, 2003; Yamamoto & Shelton, 2009), little is known about the roles of these senses for implicit context learning. Concerning the haptic/tactile sense, a growing, although still modest, number of studies have revealed intricate processing capabilities of this modality. For example, it has been demonstrated that features such as material dimensions and abrupt surface discontinuities are likely to produce low search function slopes, suggesting a parallel search, whereas orientation and 3-D surface contours are likely to yield somewhat steep slopes, suggesting serial search (Lederman & Klatzky, 1997). More recently, a study focusing on a manual 3-D search task demonstrated that saliency was an important factor in determining what parts of the hand and what strategies would be used to contact the target, suggesting that nonsalient conditions made participants more likely to engage the thumb in a serial strategy, whereas in salient target conditions, parallel strategies such as grasping and shuffling of the items in the hand were applied (van Polanen, Bergmann Tiest, & Kappers, 2014). With respect to spatial learning and representations, it has been claimed that the haptic sense can facilitate (the updating of) visuospatial representations (Shelton & McNamara, 2001), or even that participants are able to form entirely new spatial representations in an explicit learning task on the basis of haptic information alone (Pasqualotto, Finucane, & Newell, 2005). However, whether the tactile sense is capable of forming its own *implicit spatial representation* and the extent to which such representations can be used for attentional guidance remain open questions. This is the issue that we investigated in the present study.

Hitherto, to our knowledge, only one study, by Nabeta, Ono, and Kawahara (2003), has attempted to investigate haptic contextual cueing. Nabeta et al. found facilitation of RTs for old relative to new *haptic* arrangements when the old (haptic) arrangements were learned in a preceding visual search task (i.e., the same arrangements were used in visual and haptic tasks). However, it was not clear whether this haptic contextual-cueing effect was driven by haptic or visual representations. That is, they could not rule out that in the haptic task, participants may have continued to operate an essentially visual strategy (see, e.g., Lederman, Klatzky, Chataway, & Summers, 1990, for the effects of visual imagery on recognition performance in a haptic discrimination task). For example, participants may have registered the haptically sensed stimuli in a visuospatial representation maintained in working memory, and it may have been this representation that, when critical (context) stimuli had been sampled and recorded, triggered the matching visual context information stored in long-term memory, thus guiding haptic search to the (visually represented) target location. Note that Nabeta et al.'s participants did not see the haptic displays, so search could ultimately only be based on some actively built-up and maintained spatial working memory representation. In other words, the observed haptic contextual cueing might well have been visually mediated. Furthermore, Nabeta et al. did not address the fundamental question: that is, whether contextual regularities can also be acquired in—rather than in one way or another "transferred" to—the haptic modality. The present study was designed to examine this question.

Participants were tested in an exclusively tactile search task, which adopted Chun and Jiang's (1998) original approach, with half of the trials containing old and the other half new arrangements. In Experiment 1, we investigated contextual cueing in tactile search, whereas in Experiment 2 we assessed participants' explicit knowledge of repeated tactile arrangements. In Experiment 3, we introduced a discrimination task in order to dissociate the contextual cueing of target selection from the contextual cueing of response selection.

Experiment 1

Method

Participants Nine naïve participants (eight female, one male, eight right-handed; age range 24 to 41 years) took part in this experiment for either course credit or €8.00/h. All of the participants reported normal tactile perception and no history of somatosensory disorders. Participants gave informed consent prior to performing the experiment, which was approved by the ethics committee of the Department of Psychology at LMU Munich, in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Apparatus and stimuli The vibrotactile stimuli, 100- and 30-Hz vibrations, were generated by eight solenoid actuators that activated lodged cylinder metal tips when the solenoid coils were magnetized (Heijo Box, Heijo Research Electronics, UK; see Fig. 1). The maximum finger contact area was about 2–4 mm. The eight actuators, connected to a "standard" PC via parallel port, were controlled by a purpose-written MATLAB program in combination with the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). Participants' responses were recorded via foot pedals. In the practice phase, visual information such as instructions, fixation cross, and response feedback was video-projected onto a semitransparent Plexiglas table (size, 70 × 60 cm; height, 84 cm) by a projector (Sharp XR-32X-L), and was therefore available for the participants to monitor. In the experimental phase, a blindfold was used to prevent participants from seeing the tactile arrangements (and thus to avoid visual learning of the tactile arrays). Furthermore, the vibrotactile stimulations were masked by white noise (1000 Hz, ~65 dBA, 3,000 ms or until response execution) delivered via cushioned ear shell headphones (Philips SHL4000, 30-mm speaker drive). This was again done in an attempt to rule out confounding factors in the determination of participants' performance, such as auditory learning of the tactile arrays: Note that different vibrotactile stimulations generate different tones, thus potentially offering an additional, auditory source of information for configural learning.

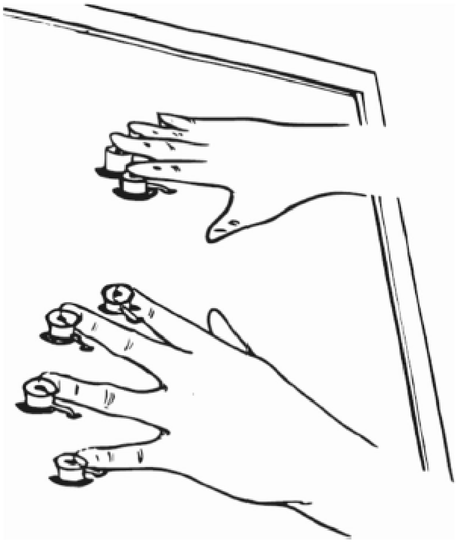

Fig. 1 Illustration of the experimental setup. Participants placed their fingers (except the thumbs) on eight solenoids delivering tactile stimulation. The solenoids are indicated by the rings in the figure. In Experiments 1 and 2, participants indicated the location of a feature-singleton target, defined by a different frequency relative to the distractors, as being delivered to a left- or a right-hand finger by pressing the corresponding (left or, respectively, right) foot pedal. In Experiment 3, participants indicated the target identity using the appropriate foot response, regardless of the hand or finger stimulated

Procedure Following written and verbal instructions, participants were equipped with headphones, and, once they were comfortably seated on a chair with their forearms on the table, gently placed their fingertips (except the thumbs) on the stimulators. Prior to the practice session, the positions of the stimulators were adjusted to fit the participant's fingers. In order to maximize comfort, participants chose whether or not they wanted to use a cushion as a wrist-rest throughout the experiment.

Practice session Each trial of the practice session started with a foot press and included stimulations delivered to seven distractor fingers vibrating at 100 Hz and one target finger vibrating at 30 Hz. All stimulators vibrated until a response was made or up to 3,000 ms, whichever came first. In doing so, the target was presented four times at any of the eight fingers, yielding 32 practice trials in total. Note that, given the limited number of tactile configurations available for the experimental session (see below), the practice session used stimulations of all eight fingers. The idea was to familiarize participants with the tactile search task—that is, target-versus-distractor discrimination in general—rather than the learning of specific tactile arrangements. Participants' task was to localize the target, as quickly as possible, on the left or the right hand by pressing the spatially corresponding foot pedal. Following participants' responses, accuracy feedback was provided by presenting the words "correct" or "wrong" on the Plexiglas plate (duration: 1,000 ms). Participants were instructed to monitor this feedback and use it to improve their tactile search performance. Thus, emphasis was placed on both response speed and accuracy.

Experimental session Following the instructions, participants started the experimental session by a foot press. Both the tactile vibration and white auditory noise were presented simultaneously until a response was made or up to 3,000 ms. Importantly, unlike in the practice session, in the experimental session participants were wearing a blindfold so that they did not see their fingers, thus preventing concomitant visual learning of the repeated tactile arrangements. Participants were asked to respond to the target side (either the left or the right) as quickly and accurately as possible by pressing the corresponding foot pedal. The next trial was automatically initiated following an intertrial interval of 1,000 ms.

Design The design of Experiments 1–3 was adapted from that of Chun and Jiang (1998). On each trial of the experimental session, the tactile configuration consisted of stimulations of one target and three distractor fingers. To balance the vibrotactile stimulations between the two hands, a given tactile configuration always involved one hand with two distractors and the other hand with one distractor and one target (see Fig. 2). A set of four old configurations was randomly generated for each participant. For these old configurations, the relationship between the target and distractors was kept constant throughout the entire experiment (a block consisted of a set of four old plus four new configurations). The new configurations, by contrast, were newly generated in each block by distributing the three distractors anew across the remaining fingers of each hand on each new trial. Importantly, in the new condition, too, the four target fingers were held constant throughout the experiment. Thus, four fingers were used for targets in the old configurations (two fingers on each hand), and four fingers for the new configurations (again, two fingers on each hand). In doing so, participants had no bias to search for a target at specific fingers, since each finger was equally likely to contain a target. Performance gains in the old condition could therefore only be attributed to the effects of repeated tactile arrangements, rather than repeated absolute target locations. The latter were equated across the old and new tactile conditions. The experiment consisted of 128 trials, divided into 16 blocks. At the end of every second block, the white noise was interrupted, followed by the presentation of a brief double beep (2 × 200 ms, 1000 Hz, ~72 dBA; separated by an 800-ms silent interval), indicating that the participants could take a short break and resume the experiment (by a foot press) whenever they were ready to continue. The entire experimental session lasted about 30 min.

Results

In order to increase statistical power, the data of two consecutive blocks were pooled together into one epoch (see Chun & Jiang, 1998), resulting in eight experimental epochs. For RTs, trials on which participants made an erroneous response or RTs were below 200 or above 3,000 ms (i.e., when no response was made) were excluded from the analysis (overall, 10.5 % of trials). The error and RT data were examined in repeated measures analyses of variance (ANOVAs), with any effects Greenhouse–Geisser corrected when sphericity was violated.

RT performance A 2 × 8 factorial repeated measures ANOVA on the RTs revealed a significant main effect of configuration, $F(1, 8) = 8.29$, $p < .05$, $\eta_p^2 = .509$: Targets embedded in old configurations were detected significantly faster than those embedded in new configurations (849 vs. 952 ms), indicative of a tactile contextual-cueing effect (of 103 ms).[1] Furthermore, RTs were relatively constant across experimental epochs [nonsignificant effect of epoch: $F(7, 56) = 0.469$, $p = .673$]. Although the Configuration × Epoch interaction was nonsignificant, $F(7, 56) = 0.737$, $p = .642$, additional t tests showed no difference between the RTs for old and new configurations in Epochs 1 and 2 (both $ps > .2$; see also Fig. 3). From this, one can conclude that reliable tactile contextual cueing developed over the course of the tactile search task.

Error analysis A 2 × 8 factorial repeated measures ANOVA on the error rates with Configuration (old vs. new) and Epoch (1–8) as factors failed to reveal a significant effect of configuration, $F(1, 8) = 3.85$, $p = .08$, $\eta_p^2 = .325$. Because errors made in new configurations (13.80 %) were almost twice as high as those made in old configurations (7.20 %), we ran an additional (two-tailed) t test comparing the RTs between "old" and "new" response error trials in order to identify any possible speed–accuracy trade-off in the data. This test failed to reveal a significant effect of configuration, $t(8) = 1.24$, $p = .247$. Furthermore, the ANOVA revealed the effect of epoch to be significant, $F(7, 56) = 2.31$, $p < .05$, $\eta_p^2 = .225$, reflecting a decrease in the number of errors as the experiment progressed. The interaction between configuration and epoch did not reach statistical significance, $F(1, 7) = 0.569$, $p > .778$.

Discussion

Experiment 1 employed a tactile search task in order to test whether tactile spatial context can be learned under exclusively tactile search conditions. The results provide clear evidence for this hypothesis. First, RTs were faster in old than in new tactile arrangements, an effect that became reliable after three epochs of learning (i.e., after five or six repetitions of each tactile configuration). Second, fewer response errors were made in old than in new tactile configurations (although this

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[1] In a control analysis, we examined the variability in distractor positions, measured as the standard error (*SE*) of the RTs in old and new configurations. It was possible that at least parts of the RT difference between the two types of configurations could be attributed to greater variability in distractor positions in the new configurations (in addition to contextual cueing of haptic search in the old configurations). However, a t test comparing the *SE*s between the new and old configurations was nonsignificant: $t(8) = 1.39$, $p = .202$. Similar results were obtained for Experiment 2 [$t(11) = 0.000$, $p = 1.00$] and Experiment 3 [$t(13) = 1.52$, $p = .15$]. This ruled out the alternative account.

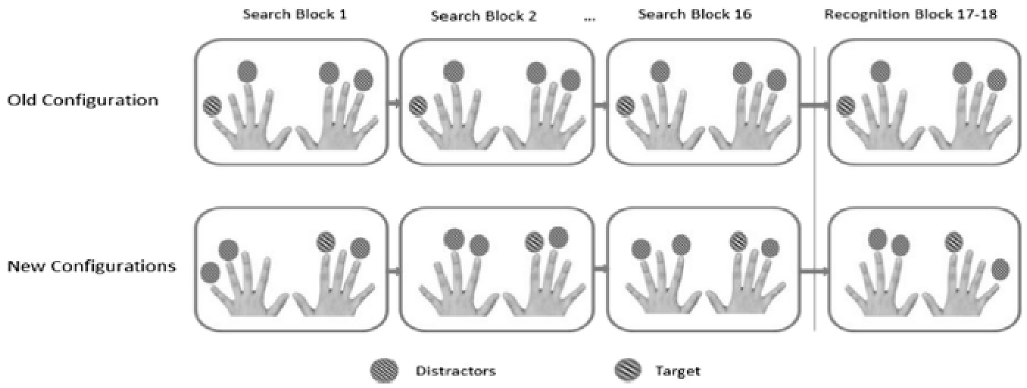

Fig. 2 Schematic figure displaying the distribution of items in old and new configurations across search epochs (and the recognition task, for Exps. 2 and 3). In old configurations, the target location is constant and paired with constant distractor locations; in new configurations, by contrast, only the target location is held constant across repetitions

effect was nonsignificant), and the higher error rate in the latter condition was not due to a speed–accuracy trade-off. Nevertheless, response errors in both conditions decreased as the experiment progressed, as we observed in the main effect of epoch on response accuracy. Altogether, Experiment 1 provided evidence for context-dependent tactile learning, reflected by faster RTs in old than in new tactile arrangements and (numerically) fewer response errors to old arrangements. Context-independent procedural learning was also observed, reflected by a general reduction of error rates across experimental epochs.

A highly debatable claim in *visual contextual cueing* is whether the effect is supported by implicit memory (for a critical discussion, see, e.g., Schlagbauer, Müller, Zehetleitner, & Geyer, 2012, or Smyth & Shanks, 2008). Although Experiment 1 provided clear support for contextual cueing of tactile search, it left open the question of the implicit nature of the tactile contextual-cueing effect. To address this issue, in Experiment 2 we introduced a recognition test at the end of the experimental session to examine whether participants had awareness of the repeated tactile configurations.

Experiment 2

Method

Experiment 2 was a close replication of Experiment 1, with the following exceptions. In addition to implementing a recognition test, in Experiment 2 we implemented a more conservative practice regime, with the aim of reducing the relatively high rates of response errors made by participants in Experiment 1 (new configurations, 13.80 %; old configurations, 7.20 %). To this end, in Experiment 2 participants were informed that they would proceed from the practice to the experimental session only after having attained a minimum of 80 % correct responses in the practice session.

Participants Fourteen new participants took part in Experiment 2 (seven female, seven male, 13 right-handed; age range 19 to 34 years). The criteria for participation, payments, and ethical guidelines were the same as in Experiment 1. Two participants were excluded because

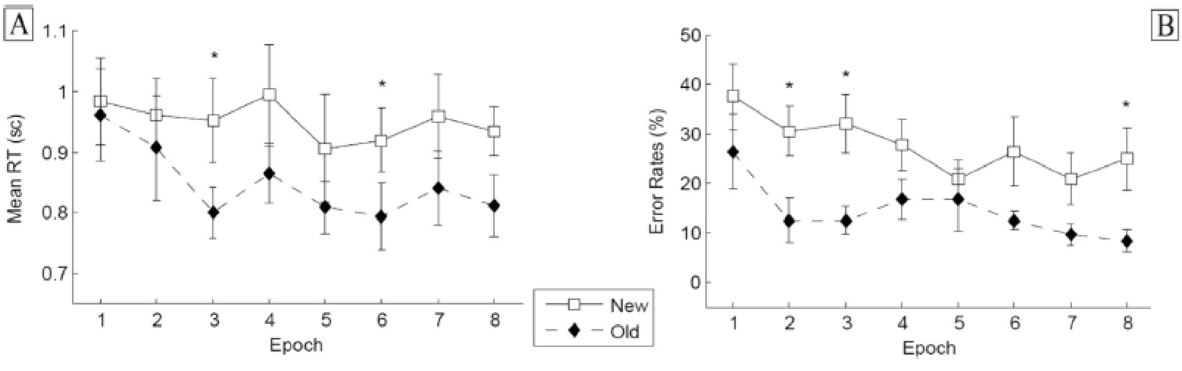

Fig. 3 Experiment 1: **a** Mean response times across epochs for old and new configurations, with error bars representing within-participants standard errors of the means (Cousineau, 2005). **b** Mean error rates across epochs, shown separately for old and new configurations, with error bars representing standard errors of the means. $^{*}p < .05$

they showed unusually large contextual-cueing effects already in the first experimental epoch. A post-hoc analysis revealed that for these two participants, just by chance, the target fingers in old and new configurations were chosen in such a way that they were symmetrically allocated across hands, with old targets being presented at Fingers 2 and 4 and new targets at Fingers 1 and 3 of the left and right hands, respectively. This may have fostered the coupling of targets with specific (old, new) distractor arrangements. The percentage of trials excluded due to incorrect responses was 6.70 %. Outliers occurred in 0.06 % of all trials (i.e., RTs below 200 and above 3,000 ms).

Procedure For the practice session, in addition to visual feedback, incorrect responses triggered an "error warning" beep (2500 Hz, ~85 dBA, 900 ms), followed by a silent intertrial interval of 2,000 or 2,500 ms. Furthermore, overall accuracy feedback was provided visually by displaying to participants their mean correct response rate after every second practice block (of 16 trials). Participants were asked to aim for a minimum of 80 % correct in at least three consecutive practice blocks. The experimental session was similar to that of Experiment 1, except for the use of "error warning" beeps following response errors. The entire experimental procedure lasted about 30–40 min.

Recognition task At the end of the experimental session, participants performed a "yes–no" recognition task, meant to assess their explicit knowledge of the repeated tactile configurations. The recognition test consisted of 16 trials: 4 × 2 old and 4 × 2 new configurations, presented in randomized order, with the exception that a given display was never shown repeatedly on two consecutive trials. Because each old configuration was presented twice, each new configuration was also presented twice in order to equate the repetition effects across the two types of configurations.

Results

RT performance A 2 × 8 factorial repeated measures ANOVA on the RTs revealed a significant main effect of configuration, $F(1, 11) = 6.02$, $p < .05$, $\eta_p^2 = .354$: Targets embedded in old tactile arrangements were responded to faster than targets in new configurations (775 vs. 885 ms), resulting in a contextual-cueing effect of 110 ms. No other effects reached statistical significance [epoch, $F(7, 77) = 2.24$, $p = .14$; Configuration × Epoch interaction, $F(7, 77) = 0.853$, $p = .547$]. Regarding the nonsignificant interaction, additional t tests showed no RT difference between old and new configurations in Epochs 1 and 2 ($p>.1$; see Fig. 4). This outcome suggests that, as in Experiment 1, tactile contextual cueing developed as the experiment progressed.

Error analysis As in Experiment 1, a 2 × 8 factorial repeated measures ANOVA on response accuracy failed to reveal a significant effect of configuration, $F(1, 11) = 3.32$, $p = .09$: Given that participants again made fewer errors when searching for targets in old (2.34 %) than in new (4.36 %) configurations, a further t test comparing the RTs on error trials between old and new configurations was performed. Once again, the t test failed to reveal a significant effect of configuration, $t(8) = 1.75$, $p = .117$, again ruling out a speed–accuracy trade-off. No further effect reached statistical significance [epoch, $F(7, 77) = 0.662$, $p = .703$; Configuration × Epoch interaction, $F(7, 77) = 0.581$, $p = .769$].

Recognition performance Recognition accuracy was assessed in terms of the signal-detection-theoretic measure d' (Green & Swets, 1966). For each participant, d' was computed, taking into account participants' hit rates (correct judgments of old configuration as repeated) and false alarm rates (incorrect judgment of new configuration as repeated). An explicit effect would be indicated by d' being significantly greater than zero. However, across all participants, d' was quite low (0.314) and

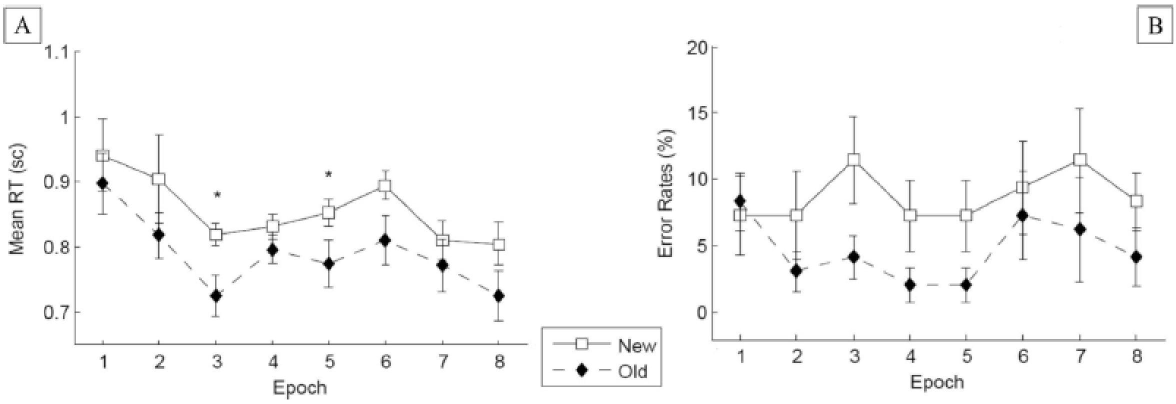

Fig. 4 Experiment 2: Mean response times (**a**) and error rates (**b**). See Fig. 3 for information about the error bars. $^{*}p < .05$

statistically indistinguishable from zero, $t(11) = 1.81$, $p = .09$, suggesting that tactile contextual cueing is an implicit effect.

Discussion

Experiment 2 replicated the tactile contextual-cueing effect found in Experiment 1, thus corroborating the idea that participants can learn repeated target–distractor arrangements in tactile search. Interestingly, the extensive practice reduced drastically the response errors in the experimental session (Exp. 2 vs. Exp. 1: old, 2.34 % vs. 7.20 %; new, 4.36 % vs. 13.80 %). Notably however, even after such a marked reduction of response errors, fewer error responses were still made to targets presented in old than in new arrays. Finally, and of the greatest importance, the results of the recognition test suggested that memory for old configurations is implicit, since participants were unable to tell apart old from new configurations.

One objection to Experiment 2 (and Exp. 1) may have been that foot responses were always congruent with the target hand. That is, after detecting an odd-one-out tactile stimulus at the fingers of a given hand (i.e., the target), it is conceivable that the corresponding foot pedal could be pressed "automatically." In other words, the RT benefit for old relative to new tactile arrangements might reflect context-based facilitation of stimulus- (i.e., hand-) to-response mapping (for the sake of simplicity, we will refer to this as the "response hypothesis"), rather than, or in addition to, contextual cueing of target selection (the "attention hypothesis"). To disentangle these alternative hypotheses, Experiment 3 introduced a discrimination task (as opposed to the localization task in Exps. 1 and 2), in which participants had to first detect and subsequently discriminate the waveform of the target signal. That is, the foot pedals were associated with the target waveform, rather than with the target hand. Under these conditions, the response hypothesis would predict no RT advantage for old relative to new tactile contexts, whereas the attention hypothesis would still predict a benefit for old arrangements.

Experiment 3

Method

Experiment 3 was similar to Experiments 1 and 2, except that it used a discrimination task. Furthermore, a new practice session was implemented in order to familiarize participants with the two different target signals.

Participants A group of 14 new participants took part in Experiment 3 (nine female, five male, 12 right-handed; age range 21 to 30 years). The criteria for participation, payment, and ethical guidelines were the same as in Experiments 1 and 2. Of all participants, only one did not provide data for the recognition test, owing to technical issues. The percentage of trials excluded due to incorrect responses was 9.3 %.

Apparatus and stimuli In order to create (three) distinct signals for targets (two signals) and distractors (one signal), the solenoid actuators were controlled by a new, 10-channel Tactor Amplifier (Dancer Design) connected to a standard PC equipped with a National Instrument Card (NI PXI-1042Q). The two possible tactile targets, T1 and T2, were defined by a square waveform manipulation of 150-Hz vibrations (Fig. 5); the distractors, by contrast, were constant 150-Hz vibrations.

Procedure The practice session was divided into two parts. In the first part, participants learned the identities of the two possible targets. One of the targets was presented in isolation per trial in a randomized fashion on each finger of each hand (except the thumbs). Furthermore, because the features of each target were rather technical for written or verbal instructions, in the first 16 trials of the practice participants received a visual cue informing them of the identity of the current target "T1" or "T2," so they could learn the physical properties and the appropriate foot response. In the second half of the practice session, participants trained on the tactile search task with one target and seven distractors (similar to Exps. 1 and 2; no visual cues as to the target identity were given). Participants were instructed to respond as quickly and accurately as possible, within 3,000 ms. They received "error warning" beeps and the intertrial intervals after erroneous responses. Of note, progress from the first to the second part of the practice session and from the practice to the test session was only possible when participants achieved 80 % accuracy in each of the two practice phases. Target pedal assignments were counterbalanced across participants: Half of participants used the left (vs. right) foot pedal for "T1" (vs. "T2"), and vice versa for the other half. The entire experimental session lasted 30–50 min, depending on participants' performance in the training session.

Recognition task At the end of Experiment 3, participants performed a "yes–no" recognition test similar to that in Experiment 2.

Results

RT performance A 2 × 8 factorial repeated measures ANOVA on the RTs revealed a significant main effect of configuration, $F(1, 13) = 5.95, p < .05, \eta_p^2 = .314$: Discrimination was faster for targets embedded in old as compared to new tactile configurations (1,373 vs. 1,416 ms), indicative of a tactile contextual-cueing effect (of 43 ms). No further effect was significant [epoch, $F(7, 91) = 2.55, p = .08$; Configuration × Epoch interaction, $F(7, 91) = .567, p = .781$]. Regarding the nonsignificant interaction, additional t tests revealed that the

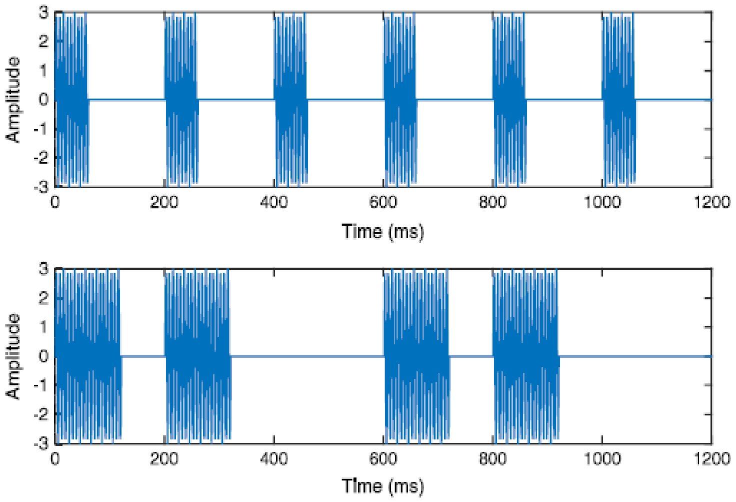

Fig. 5 Waveforms of two tactile targets. The upper panel indicates the waveform of Target 1 (T1), a 5-Hz square wave with a 30 % duty cycle delivered via 150-Hz vibrations. The lower panel shows the waveform of Target 2 (T2), a burst square wave (mean frequency of 4.17 Hz) with an average 30 % duty cycle delivered via 150-Hz vibrations. The distractors are constant vibrations of 150 Hz

RT difference between old and new configurations became significant only late in the experiment, at Epoch 6 ($p < .05$; see Fig. 6).

Error analysis A 2 × 8 factorial repeated measures ANOVA on response accuracy failed to reveal a significant effect of configuration, $F(1, 13) = 2.49$, $p = .138$. However, because participants made fewer errors when searching in old (3.9 %) than in new (6.36 %) configurations, a further t test comparing the error RTs between the two conditions was perfomed. The analysis failed to reveal a significant effect of configuration, $t(11) = 1.61$, $p = .134$, once again ruling out a speed–accuracy trade-off in the determination of the RT results. No further effect was statistically significant [epoch, $F(7, 91) = 0.139$, $p = .251$; Configuration × Epoch interaction, $F(7, 91) = 0.681$, $p = .688$].

Recognition performance Across all participants, d' was quite low (–0.17) and statistically indistinguishable from zero, $t(13) = -1.29$, $p = .218$. This result further supports the findings of Experiment 2—namely, that tactile contextual cueing is mediated by implicit memory representations.

Discussion

In Experiment 3, we examined whether RT benefits for old versus new tactile configurations were due to facilitated (learned) stimulus-to-response mappings or facilitated target selection. Employing a target discrimination task—in which different vibrotactile stimuli (T1 and T2), each of which could occur in either hand, were mapped to the foot responses—RTs were found to be still faster for old tactile arrangements. This largely rules out the possibility that the reduced RTs for

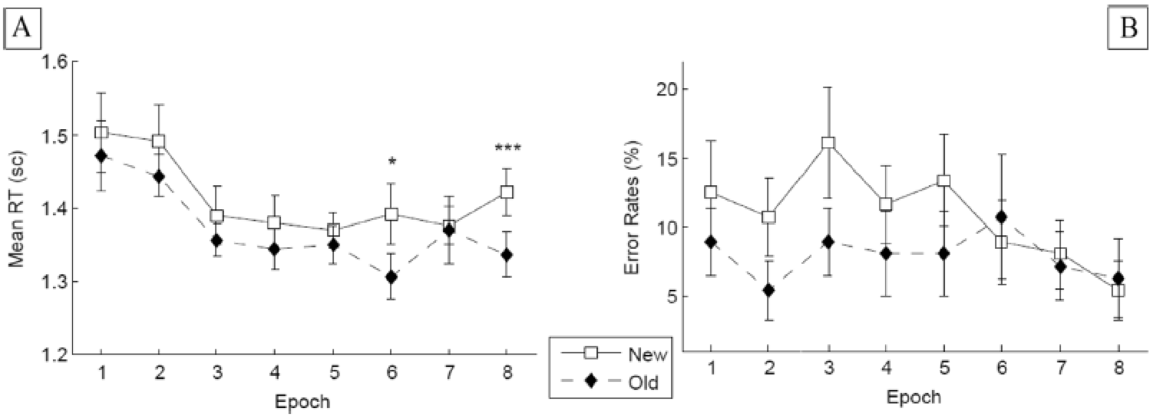

Fig. 6 Experiment 3: Mean response times (**a**), and error rates (**b**). See Fig. 3 for information about the error bars. $^{*}p < .05$, $^{***}p < .001$

repeated tactile-search arrangements are attributable to facilitation of response selection. Instead, the finding of an RT benefit for old arrangements strongly supports the alternative view of tactile contextual cueing facilitating attentional target selection (rather than postselective stimulus-to-response mapping). The analysis of error rates revealed no significant differences between old and new configurations. However, as in Experiments 1 and 2, if anything, there was a (numerical) accuracy advantage for old over new tactile arrangements in Experiment 3—that is, here, greater accuracy in discriminating, rather than localizing, the target in old configurations. This further supports the idea that configural learning did aid attentional target selection, and thus subsequent (postselective) processes of focal-attentional target discrimination. Finally, the results of the recognition test corroborate the idea that tactile contextual cueing is supported by an implicit memory, since participants were not able to tell apart old from new configurations.

It should be noted that the results of Experiment 3 do not rule out potential contributions of response selection to the RT advantages for old arrangements in Experiments 1 and 2. In fact, in Experiments 1 and 2, contextual cueing was twice as large as in Experiment 3 (103, 110, and 43 ms in Exps. 1, 2, and 3, respectively). It may well be that the reduction of the effect in Experiment 3 reflects the fact that the perfect coupling of hands and foot pedals (and learning of the couplings for repeated arrangements) in the previous experiments contributed to the overall RT advantage for old arrangements. Given that such a contribution was effectively ruled out in Experiment 3 (by making the coupling inconsistent), the tactile “contextual-cueing” effects in Experiments 1 and 2 are likely to represent an additive mixture of both facilitation of target selection and facilitation of response selection. This “hybrid view” would suggest that contextual cueing can exert a boosting influence on both target and response selection, consistent with Kunar, Flusberg, Horowitz, and Wolfe (2007), who argued for such a view in relation to visual contextual cueing.

Note that, in the present study, we inferred the effect of contextual cueing on attentional selection only indirectly, by comparing the effects of old versus new configurations between discrimination and a localization task. Thus, ideally, this evidence should be followed up in a more direct test, involving a set size manipulation or a direct measure of the brain-electrical (electroencephalographic) activity indexing the allocation of attention. Such direct tests are, however, beyond the scope of the present study, especially since they would introduce new challenges, such as whether a set size manipulation is an appropriate means for inferring attentional guidance by contextual cueing (see, e.g., Kunar et al., 2007, and Kunar, Flusberg, & Wolfe, 2008, for discussions), or which brain region provides an apt electrophysiological signal for context-based guidance in tactile search (one candidate area is the somatosensory cortex; cf. Eimer, Maravita, Van Velzen, Husain, & Driver, 2002). In the meantime, though, the important observation remains that tactile contextual cueing was reliable in a discrimination task in which there was no consistent hand- (configural-pattern-) to-foot mapping. This strongly suggests that response selection cannot be the sole source of the contextual-cueing effect. Instead, the effect also involves a component of attentional guidance.

General discussion

In the present study, we aimed at answering two questions: First, can contextual cueing arise from repeated exposure to purely tactile search configurations? And second, is tactile contextual cueing an implicit effect? Three experiments were conducted to answer these questions. The aim of Experiment 1 was to test whether contextual cueing, an effect hitherto examined almost exclusively in the visual domain, would also operate in tactile search. Experiment 2 was, additionally, designed to assess participants’ explicit knowledge of the repeated tactile configurations. And in Experiment 3 we aimed at dissociating the effects of old (vs. new) tactile arrangements on attention and response selection. The results were as follows: Response speed and accuracy were improved for old relative to new configurations in all three experiments, indicating that memory for repeated tactile configurations is acquired and subsequently expressed in tactile search. Furthermore, participants’ ability to distinguish the old from the new configurations was only at chance level, indicative of tactile contextual cueing being supported by an implicit memory system (Exps. 2 and 3). Moreover, contextual cueing was observed to be sufficiently strong to aid performance even in a target discrimination (rather than only in a target localization) task (Exp. 3). Taken together, these findings show that the tactile system is able to develop its own context representations and use these representations to guide tactile search. Furthermore, the build-up of memory for repeated tactile configurations is an automatic process, in that it does not require explicit knowledge of any repeated configurations.

To our knowledge, the present findings are the first to show that invariant spatial configurations presented exclusively to the tactile modality can be learned and can subsequently facilitate tactile search. To date, only one study has demonstrated effects of learned configurations (context) in tactile search. According to Nabeta et al. (2003), contextual knowledge acquired solely within the visual modality can subsequently facilitate haptic search. However, as we pointed out in the introduction, the results of Nabeta et al. are open to alternative interpretations, such as that haptic contextual cueing is mediated by a visuospatial representation that may trigger learned visual context associations to guide haptic search. Most importantly, Nabeta et al. did not directly address the issue of information to be retained from the sensory environment and to persist over time. These implicit memory traces contribute to the guidance of attention in the real-time processing of the perceptual array, making processing efficient by reducing the need for capacity-limited, top-down-controlled mechanisms.

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