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Remembering Touch: Using Interference Tasks to Study Tactile and Haptic Memory

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INVESTIGATING OUR SENSE OF TOUCH

We are rarely aware of using our memory for touch and yet research suggests that we are efficient—perhaps surprisingly so—at storing and subsequently accessing memories of how something felt to us. In some cases we may do this explicitly, for example, when deciding whether a melon is ripe or a cake is cooked, but in many more cases we are probably not aware that we are reactivating memories of things that we have touched. Relatively little research has been conducted on memory for touch compared with visual and auditory memory. The proportion of papers on memory for each modality has been stable, with around 70% of search results for visual plus memory, 20% for auditory plus memory, 5% for olfactory plus memory, and less than 5% in total for tactile, haptic, and gustatory plus memory.[1] Gallace and Spence (2009) provided a review of the literature on haptic and tactile memory. More recently, Wang, Bodner, and Zhou (2013; see also Wang et al., 2012) reviewed the neural basis of tactile working memory. Here, we focus on the empirical findings from previous interference studies investigating short-term and working memory for touch and also on evaluating this methodology. We then present two studies investigating interference effects on haptic memory for three-dimensional (3D) objects. In the literature there is some inconsistency in the use of the terms *tactile* and *haptic* perception. In the current chapter, *tactile* refers to passive touch (such as an experimenter pressing a shape against the palm of a participant's hand) whereas *haptics* refers to active touch, in which participants move their body to feel a stimulus (for example, by grasping a mug).

COMPARING MEMORY FOR VISION AND FOR TOUCH

As a likely consequence of the overwhelming concentration on visual and auditory memory, research on tactile and haptic memory has largely focused on comparing performance across modalities. There are difficulties in making direct comparisons across the modalities but it is clear that our sense of touch can efficiently perceive a number of important physical features, such as shape, size, and texture, which can also be extracted by vision. It is therefore possible to devise studies (e.g., Lawson, 2009) for which at least the physical stimuli presented and the perceptual information available from them are better matched than is possible for any other pair of modalities. However, even if this is done, the nature of exploration and information extraction remains fundamentally different across vision and touch. Specifically, vision can detect information at a distance and across a wide area in parallel, whereas touch

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[1] Searches were conducted for both the title only and for the abstract using the PsycINFO database and using the University of Liverpool's Web of Science database for the twentieth century and its database for 2000 to 2013.

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is typically restricted to the exploration of near space and to the sequential accumulation of information. Researchers have sometimes tried to reduce these differences, for example, by slowing down the extraction of visual information by forcing participants to view a scene using a small, movable aperture, to try to equate the load on working memory across vision and touch (Craddock, Martinovic, & Lawson, 2011; Loomis, Klatzky, & Lederman, 1991; Martinovic, Lawson, & Craddock, 2012; Monnier & Picard, 2010). However, such measures may artificially handicap processing in one or both senses, reducing the ecological validity of these studies. For example, the only visual stimuli that typically require multiple saccades to be encoded are large-scale scenes.

Differences in working memory load could explain much of the variation in performance, both when comparing across vision and touch and when contrasting different tasks involving touch. As an extreme example, the haptic exploration of two-dimensional (2D) shapes such as raised line drawings is typically extremely slow, effortful, and sequential (Lawson & Bracken, 2011); exploration times exceeding 1 min are commonplace. Building up representations of such stimuli would be expected to involve a substantial load on working memory. Overvliet, Wagemans, and Krampe (2013) found that older adults were worse at recognizing 2D raised line drawings haptically, whereas several studies have indicated that the haptic recognition and matching of 3D objects is similar for older and younger adults (Ballesteros & Reales, 2004; Norman et al., 2006, 2011). According to the image mediation model, sequentially acquired 2D haptic inputs must be translated into visual images that can then be identified using the normal visual processing system (Klatzky & Lederman, 1987; Lederman & Klatzky, 1990; Lederman, Klatzky, Chataway, & Summers, 1990). Haptic recognition of 2D shapes is therefore likely to put a much greater demand on working memory than when recognition is easier, for example for everyday 3D objects, where processing may be mediated directly by the haptic system.

As mentioned, it is possible to try to reduce the differences between vision and touch with respect to the spatiotemporal accumulation of information. For example, visual performance can be matched to be similarly slow and inaccurate as touch. Martinovic et al. (2012) attempted to determine whether haptic object identification was relatively slow and inaccurate compared with vision simply because haptics acquires information serially and more slowly than vision. This difference could in turn result in a greater working memory load for haptics than for vision. The alternative hypothesis is that there are more fundamental processing differences between haptics and vision. To address this issue, we slowed visual processing using a restricted viewing technique in which people moved one finger around on a touch screen to control an aperture that enabled them to see only a small area of the object at a time. We determined the aperture size required to achieve similar recognition performance across vision and touch (Craddock et al., 2011). We then conducted an electroencephalographic experiment to compare the time course of visual and haptic object recognition (Martinovic et al., 2012). Participants had to discriminate familiar (nameable) from unfamiliar (unnamable) objects either visually via aperture viewing or haptically. Mean response times were around 5 s for familiar objects and 9 s for unfamiliar objects in both modalities. We analyzed the evoked and total fronto-central theta-band (5–7 Hz; a marker of working memory) and the occipital upper alpha-band (10–12 Hz; a marker of perceptual processing) locked to stimulus onset. Long-latency modulations of both theta-band and alpha-band activities differed between familiar and unfamiliar objects in haptics. Decreases in total upper alpha-band activity for haptic identification of familiar relative to unfamiliar objects suggested that multisensory extrastriate areas were involved in object processing (see also Deshpande, Hu, Lacey, Stilla, & Sathian, 2010; Lacey, Flueckiger, Stilla, Lava, & Sathian, 2010 for complementary results from functional magnetic resonance imaging studies). In contrast, theta-band activity showed a general increase over time for the slowed-down visual recognition task. Our results suggested that visual and haptic object recognition share some common representations, but, importantly, there are fundamental differences between the senses that are not simply a result of differences in their usual speed of information extraction.

Notwithstanding the technical difficulties in comparing vision and touch, several studies have found efficient cross-modal recognition across these two modalities (Bushnell & Baxt, 1999; Easton, Srinivas, & Greene, 1997; Lacey & Campbell, 2006; Lawson, 2009; Newell, Ernst, Tjan, & Bülthoff, 2001; Norman, Norman, Clayton, Lianekhammy, & Zielke, 2004; Ballesteros & Reales, 1999). Furthermore, this can be done with novel, unfamiliar objects that are difficult to distinguish verbally (see Lawson, 2009), and so cross-modal performance does not have to rely on a verbal strategy involving naming the objects. Cross-modal recognition is likely achieved by integrating visual and haptic representations into a single, multisensory representation accessible to both vision and touch (Lacey, Pappas, Kreps, Lee, & Sathian, 2009).

In a further step, this evidence showing excellent cross-modal visuo-haptic processing, together with the similarity in the processing goals of vision and touch (Lawson, 2009), the importance of spatial encoding in vision and touch (Millar, 1999), and the general superiority of visual processing, has led some to assume that inputs from touch must be recoded into visual representations to be interpreted and stored (Klatzky & Lederman, 1987). However, there is now clear evidence against strong versions of such image mediation accounts (Lederman et al., 1990). For example, studies have shown that congenitally blind individuals can still recognize objects efficiently by touch despite having no visual processes available (e.g., Pietrini et al., 2004). Furthermore a number of studies have concluded that congenitally blind people as well as blindfolded sighted people can use mental imagery and working memory to perform haptic tasks requiring spatial transformation of the input (e.g., Aleman, van Lee, Mantione, Verkoijen, & de Haan, 2001; Marmor & Zaback, 1976). Nevertheless, there is good evidence that haptic shape perception is often mediated by visual imagery, as reviewed by Lacey and Sathian (2013, 2014). In a series of articles, Sathian and colleagues (Deshpande et al., 2010; Lacey et al., 2010, 2014) showed that haptic perception of unfamiliar shape and visual-spatial imagery share a common network whereas haptic perception of familiar shape and visual-object imagery share a different common network (see Kozhevnikov & Blazhenkova, 2013; for a discussion of visual-object and visual-spatial imagery differences).

MEMORY FOR TOUCH

The visual and auditory memory literature has traditionally divided memory into separate component systems such as sensory memory and short-term, long-term, and working memory (Cowan, 1995, 2001, 2008; Linden, 2007). Sensory memory refers to the registers for veridical, modality-specific representations that provide the first memories of inputs to each of our senses. These representations have limited capacity and degrade rapidly over a few seconds (Sinclair & Burton, 1996). They cannot be maintained through rehearsal. Any information to be retained must be transferred from sensory memory to short-term memory. This is another limited capacity store that can retain information for at least around 30 s without rehearsal and for longer with rehearsal (Hill & Bliss, 1968; Sinclair & Burton, 1996). Working memory refers to one component of the short-term memory system that can maintain, rehearse, and actively manipulate sensory information (Baddeley, 2000, 2007; Baddeley & Hitch, 1974). Sensory memory, short-term memory, and working memory are all limited-capacity, temporary stores. Any information that is not transferred from them into long-term memory will soon be lost. Long-term memory, in contrast, has an extremely large capacity and allows information to be stored for many years. We will use these broad distinctions to provide a convenient framework for organizing our review of research on haptic and tactile memory. However, there is no consensus as to whether these distinctions reflect meaningful theoretical divisions (Cowan, 2008; Engle, Tuholski, Laughlin, & Conway, 1999).

In the following sections we will start by briefly reviewing evidence about the most transient and then about the most durable memories for touch (sensory memory, then long-term memory). We will then focus in more detail on the use of interference studies to investigate short-term memory and working memory for touch. Finally, we will describe the results of two new studies investigating the effects of different interference tasks on haptic object recognition.

SENSORY MEMORY IN TOUCH

A number of studies have investigated the capacity and duration of our initial memories for inputs from touch, inspired by Sperling's (1960) studies of visual sensory memory. Bliss, Crane, Mansfield, and Townsend (1966; Hill & Bliss, 1968) investigated sensory memory in touch using a partial report paradigm with air-jet stimulators to three locations of each finger on both hands. Participants could recall around 3.5 positions of the air-jets for full report and around one extra position for partial report. This advantage for partial over full report indicated that there was sensory memory for tactile inputs and that this memory degraded after about 1 s. The benefit for tactile partial report seemed to be much smaller than that for visual partial report. However, participants had to learn to map each of 24 locations to a different letter, so deciding on a response was demanding. This task may thus have measured more complex processing than just immediate tactile memory.

More recently, and using a simpler task, Gallace, Tan, Haggard, and Spence (2008) assessed memory for the location of vibrations over the body using whole report (numerosity judgments) and partial report (spatially cued). Participants recalled up to three stimuli in the whole report condition and up to five using partial report. There was also a trade-off between the number of stimuli presented and the duration of the representation, with faster decay as the number of stimuli increased. Similarly, Auvray, Gallace, and Spence (2011) found that only three item locations could be reported in a full report condition of a tactile short-term memory task whereas up to six items could be recalled using partial report. They also found an overall cost to performance of concurrent articulatory suppression but no interaction with stimulus onset asynchrony, which suggests that verbal mediation did not have an important role in this task.

The whole report capacity of tactile memory for around three spatial locations and its greater capacity for partial report (Auvray et al., 2011; Bliss et al., 1966; Gallace, Tan, & Spence, 2006; Gallace et al., 2008) are similar to the limits of accurate judgments of numerosity for vision (i.e., the limits of subitization) (Ester, Drew, Klee, Vogel, & Awh, 2012; Piazza, Fumarola, Chinello, & Melcher, 2011) which may in turn reflect the capacity of visual working memory, which is also around three (e.g., Anderson, Vogel, & Awh, 2011). However, it remains possible that performance on these spatial location tasks relies on verbal recoding and as such, their results may not reflect people's ability to store purely tactile information (Bancroft, Hockley, & Servos, 2012).

Other approaches have been used to study the capacity and durability of memory for touch. Heller (1987) traced numbers onto people's hands and estimated digit span as up to seven at a slow presentation rate. A number of studies have exploited the suffix effect to compare sensory memory across different modalities. The suffix effect involves presenting an extra item immediately after a to-be-remembered list of items. In a typical, no-suffix control condition for auditory presentation there is a strong recency effect (i.e., superior recall for the final items relative to items in the middle of the list) whereas the recency effect only occurs for the last item for visual presentation. In suffix conditions, however, auditory responses are like visual responses, with no recency or recency only for the last item (e.g., Conrad & Hull, 1968). Watkins and Watkins (1974) touched participants' fingers with a pen and asked them to recall the order of presentation. Recall in control conditions showed a recency effect that disappeared after a tactile suffix, similar to the auditory suffix effect (see also Mahrer & Miles, 1999, 2002). This tactile suffix effect was confirmed by Manning (1980) using letters and nonverbal stimuli. These results suggest that a short-term, tactile sensory memory is available after a stimulus has been presented but that it is eliminated by the presentation of a subsequent tactile stimulus. This conclusion is consistent with results of Nairne and McNabb (1985), who found greater recency with recall of tactile compared with visual sequences.

Together, these studies confirm the existence of a limited-capacity, rapidly decaying, and easily overwritten sensory store for touch similar to the iconic and echoic memory stores proposed for visual and auditory inputs, respectively. The advantage of partial report over whole report appears to be smaller for tactile than for visual presentation and more similar to that for auditory presentation. In addition, the recency effect may be greater for tactile and auditory presentations than for visual sequences. These consistent differences across the modalities may reflect their relative reliance on serial versus parallel processing (e.g., Loomis et al., 1991). However, no firm conclusions can be made without conducting more direct comparisons across the modalities while controlling for variables such as stimulus familiarity and complexity. In addition, the results need to be interpreted with caution because performance in some of these tasks may rely on stored verbal or spatial information instead of, or as well as, exclusively tactile or haptic information (see Gallace & Spence, 2008, 2009; Mahrer & Miles, 2002).

LONG-TERM MEMORY IN TOUCH

One means of assessing long-term memory for touch is to measure our ability to name everyday objects because this requires people to access representations of those objects stored before the start of an experiment. Several studies indicate that we are good at recognizing 3D familiar objects using touch alone (Craddock & Lawson, 2008, 2009a, 2009b; Klatzky, Lederman, & Metzger, 1985; Lawson, 2014). We remain fast and accurate even when non-shape cues such as size, texture, and temperature are removed by presenting plastic scale models of objects and when fine shape discriminations are required: for example, between a typical chair and a bench-chair morph (Lawson, 2009, 2014). Across a range of studies it has been found that haptic object naming is usually possible in 2–6 s with 4–12% error rates. In contrast, response times for naming raised line drawings of familiar objects are often over 60 s and error rates are typically 50–90%, indicating that depth information is crucial for efficient haptic recognition (Lawson & Bracken, 2011). Overall these results indicate that we can readily encode haptic inputs from 3D objects and match these to stored object representations (although we may struggle to encode and interpret 2D stimuli). Furthermore, our sensitivity to perceptual manipulations such as rotations in depth and size changes (Craddock & Lawson, 2008, 2009b; Ernst, Lange, & Newell, 2007; Lawson, 2009, 2011; Newell et al., 2001) and differences between visual versus haptic presentation (Lawson, 2009) argue against haptic object recognition simply being mediated by stored visual or verbal rather than haptic representations.

Few studies have directly investigated the longer-term memory representations used in haptic perception. In one study Nabeta and Kusumi (2008) compared memory across touch and vision. They presented either 100 or 500 everyday objects at study. A subset of these old items together with new objects with different names was then presented in an old/new recognition test. Performance in both modalities was excellent and suggested that memory capacity easily exceeds 500 objects in both haptics and vision. Surprisingly, haptic memory was superior to visual memory, which provides further evidence that long-term haptic memory is not mediated solely by visual or verbal representations.

Pensky, Johnson, Haag, and Homa (2008) provided the strongest evidence about long-term haptic memory. They addressed the issue of verbal recoding directly and tested retention across intervals of up to 1 week. Their results showed that people could encode stable representations of both visually and haptically presented objects. In the study, participants manipulated a set of everyday objects. Then, after 1 h or 1 week, participants performed an old/new recognition test with the study objects and distracters from the same basic-level category (e.g., two different shaped and labeled food cans). Both haptic and cross-modal recognition was well above chance even after 1 week although unimodal haptic recognition decayed faster than unimodal visual recognition. Because participants could not rely on remembering the basic-level names of the study items to succeed at the task, this finding of above-chance recognition after a week shows that long-term haptic representations of objects can be acquired. Haptic recognition was worse than visual recognition, but this may have been because the availability of features of objects was not matched across the modalities. For example, differences between the food can labels could only be perceived visually, not haptically. Thus, overall performance levels across the modalities may simply have reflected differences in the information available to vision versus to touch.

SHORT-TERM MEMORY AND WORKING MEMORY IN TOUCH

A distinction is often drawn between short-term and working memory. However, performance on tasks that supposedly reflect one or the other type of processing typically show high intercorrelations, which suggests that to a large extent, they tap a common construct (Engle et al., 1999; Swanson & Luxenberg, 2009; Withagen, Kappers, Vervloed, Knoors, & Verhoeven, 2013). In the current chapter it is not necessary to distinguish between more passive short-term memory and more active working memory. Because little work has attempted to develop distinct short-term and working memory tasks for touch, we will not separate our review of research on temporary memory for touch based on this distinction.

Temporary memory for touch over delays of several seconds is assumed to require more stable representations than those available using the sensory store. However, tactile working memory is limited in capacity, shows a fair degree of interindividual variability (Bliss & Hämäläinen, 2005), and decays between around 15 and 30 s post-stimulus (Kiphart, Hughes, Simmons, & Cross, 1992). There is also evidence that different modality-specific areas are involved in the short-term maintenance as well as the acquisition of information through vision and touch (Gallace & Spence, 2009; Seemüller, Müller, & Rösler, 2012; Woods, O'Modhrain, & Newell, 2004). It is also important to acknowledge that much research on working memory for touch used stimuli that could be visually or verbally encoded and rehearsed. This can make it difficult to determine whether performance on a specific task is underpinned by modality-specific, tactile, or haptic representations rather than visual or verbal representations. Inputs from touch may be recoded into visual or verbal representations, and indeed, they may also be encoding using motor, kinesthetic, or spatial information that is acquired when touch is used to actively explore stimuli (e.g., see Loomis, Klatzky, & Giudice, 2013; for discussion of the use of amodal spatial images in working memory). The degree to which people rely on alternative representations will likely depend on the individual, the task, and the stimuli.

Several studies have provided evidence that working memory processes occur for inputs from touch (Cornoldi & Vecchi, 2003; Mahrer & Miles, 2002; Miles & Borthwick, 1996) and that modality-specific brain areas support the retention of sensory information from touch (Harris, Miniussi, Harris, & Diamond, 2002; Ricciardi et al., 2006; but see Bancroft, Hogeveen, Hockley, & Servos, 2014). In addition, studies of congenitally blind people have shown that visual experience is not essential to support effective short-term and working memory processes such as forward and backward span tasks, the generation and transformation of spatial images, and object recognition; blind people show superior memory compared with sighted individuals in many cases (Hull & Mason, 1995; Pring, 2008; Rokem & Ahissar, 2009; Swanson & Luxenberg, 2009; Pietrini et al., 2004; Vecchi, 1998; Vecchi, Tinti, & Cornoldi, 2004; Withagen et al., 2013).

In the next sections we will focus on research on temporary memory for touch that has used an interference task methodology to determine the nature of the representations underlying performance in haptic memory tasks. We will first consider general issues arising from the use of this method before reviewing the results of research on memory for touch using interference tasks. Finally, we present two new studies that tested a range of interference tasks to investigate the type of representations used in haptic object recognition.

ISSUES ARISING FROM THE USE OF INTERFERENCE TECHNIQUES

General Principles

Interference (or dual-task) studies require participants to perform a primary task that is of interest and a concurrent secondary task that may rely on the same cognitive processes that are hypothesized to support the primary task. The extent to which performance on the primary task is impaired by the concurrent secondary task is assumed to reflect the extent to which both tasks share common processes. Interference tasks have long been used to investigate structural aspects of working memory: for example, to probe the existence and limits of its visual, spatial, and verbal subcomponents (e.g., Baddeley, Grant, Wight, & Thomson, 1975). Interference techniques have an effect by inducing competition for cognitive resources and not by reducing perceptual sensitivity. Requiring participants to monitor speech while wearing earplugs reduces performance but only by reducing perceptual sensitivity; presenting the speech to be monitored to one ear and different distracting speech to the other ear induces competition and constitutes interference.

Competition for cognitive resources between the primary and secondary tasks results in poorer performance on the primary task compared with a control, single-task condition in which there is no secondary task and also with alternative concurrent secondary tasks that do not compete for the same resources. Using multiple secondary tasks has the benefit of helping to control for the deleterious effects of divided attention and competition for general processing resources in dual-task conditions. A further advantage is that performance on each secondary task alone, without the primary task, can be measured. This allows the secondary tasks to be adjusted to try to equate their difficulty, and then this single-task performance can be compared with dual-task performance to check whether secondary task performance is disrupted in the dual-task condition.

Experimental Design in Haptic Interference Tasks

Following on from the general principles described above, the design of interference experiments needs to take into consideration a number of factors to avoid some obvious pitfalls (Cowan, 1995; Green & Vaid, 1983; Oberauer & Göthe, 2006; Pashler, 1994). Several studies of memory for touch have compared just one dual-task condition (an interference task performed simultaneously with the primary task) to a control condition (the primary task performed alone with no interference) (e.g., Gilson & Baddeley, 1969; Sinclair & Burton, 1996; Sullivan & Turvey, 1972). Here, any interference may not reflect shared task-specific processes but instead may simply reflect domain-general competition for processing capacity such as a common attentional resource. This problem can be ameliorated by using multiple different interference tasks of similar general difficulty and comparing performance across them (e.g., Lacey & Campbell, 2006). A more complex alternative, but one that avoids the problem of variation in the overall difficulty of the interference tasks, is to use multiple primary tasks (e.g., Chan & Newell, 2008); the effect of the same secondary interference tasks can then be compared across the different primary tasks.

An interesting recent approach that sidesteps these issues used transcranial magnetic stimulation (TMS) to improve performance by reducing interference in a working memory task requiring delayed tactile temporal discrimination. Hannula and colleagues demonstrated that using TMS early during the retention period to suppress irrelevant sensory processing of a distracting tactile stimulus (an electrical pulse identical to the experimental stimuli) actually improved response times in the primary working memory task (Hannula et al., 2010). This was probably because TMS reduced activity in the primary somatosensory cortex responsible for representing the distracting tactile stimuli during maintenance of the tactile temporal information for the primary task. This improvement was likely modality-specific in that TMS improved performance during tactile, but not visual, interference (Savolainen et al., 2011). However, one caveat of this latter finding is that tactile interference was greater than visual interference, so it is possible that the difference in the observed TMS effects reflected the amount of interference caused by the distracter rather than its modality.

A second factor to consider with interference studies is that the secondary task should disrupt the process assumed to be engaged by the primary task. For example, articulatory suppression (repeating the same word aloud) is assumed to prevent verbal rehearsal (Baddeley, 2000; Peterson & Peterson, 1959). However, relatively few studies have tried to assess the effectiveness of the secondary interference tasks in achieving this aim, and it is easy to employ secondary tasks uncritically. In a study of visuo-haptic cross-modal scene recognition, Newell, Woods, Mernagh, and Bülthoff (2005) concluded that the spatial relationships between the objects in the scene were not verbally recoded into a description of the scene because there was no effect of verbal interference during encoding. However, in their task, producing a scene description was a semantically and syntactically meaningful process whereas the verbal interference task merely required participants to repeat the word *the*. This would disrupt subvocal rehearsal but it would not be expected to engage semantic or syntactic processes. Thus, the interference task did not tap all of the verbal processes assumed to underlie the primary task. By contrast, Lacey and Campbell (2006) required participants to listen to task-irrelevant but semantically meaningful speech as a secondary task during encoding. The use of verbal labels for stimuli encoded by touch need not be restricted to the names of familiar items. Instead, perceptual qualities (*cold* or *bumpy*) or names reflecting similarities to known objects may support performance. Lacey and Campbell's proposal that subvocal description aided the encoding of unfamiliar objects was supported by their finding that listening to irrelevant speech selectively interfered with the haptic encoding of unfamiliar but not familiar objects. Similarly, care needs to be taken in the use of visual interference tasks. Dynamic visual noise (DVN) is often used in studies of working memory (see Quinn & McConnell, 1996, 1999, 2006; McConnell & Quinn, 2000; Andrade, Kemps, Werniers, May, & Szmalec, 2002). Such studies typically deal with the maintenance of representations that are retrieved from long-term memory and change rates in the DVN of 5–10% are enough to disrupt these stored representations. However, for perceptually derived representations, a change rate of 50% is required (Dean, Dewhurst, Morris, & Whittaker, 2005; Dean, Dewhurst, & Whittaker, 2008) and this DVN rate has been shown to disrupt both visual and haptic encoding of unfamiliar objects (Lacey & Campbell, 2006).

An important and related factor in matching the secondary interference task to the putative processes underlying the primary task is that many, if not most, interference tasks appear to tap multiple cognitive processes. This raises challenges in interpreting the cause of any interference effects found. For example, Millar (1974) required participants to trace standard shapes on the floor in one interference task and to stack 3D objects inside each other in another, whereas Ittyerah and Marks (2007) asked people to place a series of paper clips at regular intervals. All three of these secondary interference tasks included motor, haptic, and spatial components. It may be especially difficult to distinguish haptic interference tasks from motor interference tasks. One approach to resolving this issue was taken in Experiment 1 here, in which the same action (stroking strips of paper) was used in two secondary interference tasks. When no response was required, the task was labeled as motor interference, but when the paper texture had to be discriminated and responded to, it was labeled as haptic interference.

Having selected appropriate interference tasks in accordance with these points, it is important to ensure that the tasks chosen cover all of the competing hypotheses. This has not always been done. For example, Millar (1972) found no significant effect on children's visual, haptic, or cross-modal shape recognition owing to visual interference (viewing cartoon figures) or to verbal interference (digit repetition). However, haptic, motor, and spatial interference conditions were not tested and no positive evidence was revealed about the nature of the representations involved in this task. Similarly, Holtby and D'Angiulli (2012) tested verbal and visual but not haptic interference, whereas Garvill and Molander (1977) used visual and haptic matching tasks as interference but did not include verbal or spatial interference tasks. Using visual, verbal, and haptic interference tasks, Lacey and Campbell (2006) were able to distinguish, at least in part, among visual imagery, dual-code (Paivio, 1986, 2007), and amodal accounts of cross-modal recognition; however, they did not include a spatial interference condition, so this possibility was left open.

Finally, there is the question of when in time to place the interference task relative to the encoding, maintenance, and retrieval stages of the primary haptic or tactile memory task. Interference has been applied during study (e.g., Newell et al., 2005; Lacey & Campbell, 2006; Experiment 1 here), at test, when a response is required (e.g., Lacey & Campbell, 2006), or most commonly, during the study–test retention interval (e.g., Bancroft & Servos, 2011; Chan & Newell, 2008; Garvill & Molander, 1977; Mahrer & Miles, 2002; Millar, 1972; Paz, Mayas & Ballesteros, 2007; Experiment 2 here). Differences in the effects of interference at each of these three stages may simply reflect variation in the difficulty of combining two tasks. Employing interference during the retention interval is generally easier because participants are not simultaneously acquiring information or responding in the primary task, and the study may be simpler to set up because both hands are free. In addition, it is easy to vary interval duration during the retention period. However, there are theoretically well-motivated reasons to believe that different processes are influenced by interference at each stage. During encoding (study) and retrieval (test), interference can be used to investigate whether different formats of representations are involved (e.g., Lacey & Campbell, 2006) whereas interference during the retention interval can be used to examine maintenance and rehearsal mechanisms or decay functions. Even finer temporal distinctions may be important: Some studies have shown that interference effects are influenced by whether interference is applied early or late during the retention period (Bancroft & Servos, 2011; Hannula et al., 2010).

COMPARING ACROSS INTERFERENCE STUDIES INVESTIGATING TOUCH

It should already be clear that there is great variety in the secondary interference tasks that researchers have used to test short-term memory for touch. Unfortunately, tasks sometimes appear to have been chosen idiosyncratically or with no clear theoretical basis. Also many (and probably most) tasks are complex and fail to tap a single cognitive process cleanly. This makes it difficult to interpret any disruptive effects of the task and also makes it likely that different secondary tasks used in the study will both target the same process. This diversity and complexity of secondary tasks could explain apparent inconsistencies in the results found across studies that appear to use similar methods, as we discuss below.

For example, some verbal interference tasks have used simple articulatory suppression (e.g., repeating a single syllable) (Mahrer & Miles, 2002; Miles & Borthwick, 1996; Newell et al., 2005), counting aloud (Ittyerah & Marks, 2007), or passively listening to speech (Lacey & Campbell, 2006). However, many have used much harder verbal tasks: counting backward in threes (Miles & Borthwick, 1996; Millar, 1974), reciting the alphabet backward (Gentaz & Hatwell, 1999), repeating digit strings (Millar, 1972), mental arithmetic (Cohen, Voss, Lepore, & Scherzer, 2010), generating words beginning with a specific letter in Experiment 2 here, and doing a difficult non-word discrimination task in Experiment 1 here.

Visual interference tasks are similarly diverse and it is difficult to ensure that they do not also require spatial processing. Some have not required a response (e.g., looking at DVN (Lacey & Campbell, 2006)) but often they do (such as matching the hue or location of color patches (Chan & Newell, 2008)).

Spatial interference tasks have ranged from simple visual dot-tracking (Lacey & Campbell, 2006) to difficult imagery-based tasks (specifying the direction of turns around a capital letter in Experiment 2 here, or a mental rotation matching task as in Experiment 1 here). In addition, spatial tasks can be presented visually (e.g., Lacey & Campbell, 2006) (Experiment 1 here), verbally (Experiment 2 here), or haptically (feeling a matrix of blocks, imagining moving the blocks, then reporting the final block configuration) (Cohen et al., 2010). Few studies have directly compared visuospatial with haptic-spatial interference, and even when this has been done the tasks have been poorly matched across modality (e.g., Paz et al., 2007; Sebastián, Mayas, Manso, & Ballesteros, 2008).

Finally, haptic and tactile interference tasks can be passive (such as an experimenter moving a pen against the participant's fingers) (Mahrer & Miles, 2002), active but requiring no response (manipulating an object in the non-dominant hand) (Lacey & Campbell, 2006), although this might better be described as a motor task; or finding and rotating a block (Paz et al., 2007), or active with a response required (matching the orientation or texture of sandpaper (Chan & Newell, 2008), stacking objects inside each other (Millar, 1974), using both hands to move books between two stacks (Ittyerah & Marks, 2007), moving jigsaw pieces between two containers (Experiment 2 here), or discriminating between samples of paper (Experiment 1 here).

This diversity of interference tasks makes it difficult to compare across studies and the occasional lack of a clear theoretical motivation for task selection makes it hard to draw clear conclusions as to why a given pattern of interference effects occurred. Regrettably, Lacey and Campbell (2006) would confess that they were not especially clear about the rationale for choosing a verbal interference task involving continuous prose text over simple word repetition. However, lack of standardization of interference tasks is by no means restricted to dual-task research on memory for touch (e.g., see Al-Yahya et al., 2011) and creating standard tasks would take considerable work. Furthermore, despite these problems with cross-study comparisons, consistencies in results appear, as we will show later, if one contrasts studies on a like-for-like basis and takes into account when interference task occur.

USING INTERFERENCE TASKS TO INVESTIGATE SHORT-TERM AND WORKING MEMORY IN TOUCH

We have discussed a number of studies that used interference (dual) task methodology to investigate short-term and working memory for touch across a range of different primary tasks. We now describe the results of these studies to evaluate what we have learned from them. We begin with a series of studies that measured memory for the location of a tactile stimulus as the primary task.

Gilson and Baddeley (1969) asked participants to point with their finger to the location of a touch to the forearm by a pen. They responded either immediately or after delays of up to a minute. A control group performed the task alone while a second group counted backward in threes during the retention interval to prevent verbal rehearsal. The accuracy of tactile location for this second, articulatory suppression group deteriorated rapidly over time, with large errors made by delays of 45 s. In contrast, accuracy of the first, control group was relatively good up to 15 s retention and then slowly decayed (broadly consistent with Kiphart et al., 1992), and it remained superior to that of the articulatory suppression group. Presumably the dual-task interference group had to rely on transient sensory memory of the tactile stimuli whereas the single-task group benefitted from being able to transfer information from sensory memory to a more durable short-term memory store. These results were interpreted as indicating that rehearsal was an important component of this information transfer. However, the nature of this rehearsal could not be elucidated from this study; importantly, an alternative account of a general cost of divided attention cannot be ruled out because only one interference task was tested.

Miles and Borthwick (1996) failed to replicate the interaction between task and retention interval reported by Gilson and Baddeley (1969). In their first experiment, although their no-suppression control group outperformed their articulatory suppression group, accuracy in reporting the location of a tactile stimulus to the arm decayed smoothly for both groups as the retention interval increased and there was no difference between groups in this decay rate. This result is consistent with that reported by Sullivan and Turvey (1972), who also had participants report the location of a discrete tactile stimulus on the arm in a control, single-task condition or in a dual-task condition (doing simple arithmetic during the retention interval of up to 60 s). Similar to Miles and Borthwick's findings, accuracy decayed over time for both the single and dual tasks, although performance reached asymptote much sooner in Sullivan and Turvey's study, after just 5 s. Miles and Borthwick argued that if accurate recall of tactile locations relied on rehearsing verbal information, an interaction would be predicted between costs resulting from articulatory suppression and those from increasing the retention interval. Recall with articulatory suppression should decay rapidly over time as the tactile sensory trace decayed, whereas recall with no suppression should be relatively impervious to retention interval because location information could be maintained through rehearsal, as reported by Gilson and Baddeley (1969). However, they did not find this interaction; neither did Sullivan and Turvey (1972). In their third experiment, Miles and Borthwick (1996) reported that both verbal (articulatory suppression) interference and tactile interference (the experimenter moving a pen over the eight tactile test locations during the retention interval) impaired tactile memory, but that doing both of these interference tasks together caused no further drop in performance. They suggested that verbal and tactile interference impaired different processes involved in tactile short-term memory, with verbal interference reducing central processing resources and tactile interference disrupting a sensory tactile memory of the stimuli. However, they may not have had sufficient power in their study to detect differences among the three interference conditions, so this conclusion remains preliminary.

One important issue to note about the interference studies conducted by Gilson and Baddeley (1969), Miles and Borthwick (1996), and Sullivan and Turvey (1972) is that participants were asked only to recall where a tactile stimulus occurred rather than to report anything about its identity. These results, which suggest that both verbal and tactile interference disrupts memory for tactile location, therefore may not generalize to a wider range of tasks that require objects to be recognized or matched. Furthermore, there were important and unexplained differences in the findings across these short-term memory interference studies. These could result from relatively subtle methodological variation. Also, visual imagery of the tactile skin locations might have mediated performance in these studies such that, for example, effects of retention interval reflected decay of visual images rather than decay of tactile representations (Gallace & Spence, 2009).

We now move to review studies that used interference tasks to investigate haptic span as the primary task. Paz et al. (2007) contrasted visual and haptic spatial memory in young adults, older adults, and older adults with mild cognitive impairment. Working memory spans for spatial location information were smaller for haptic presentation (three to four items for young adults) than for visual presentation (five to seven items) in all three groups. However, stimulus presentation was not matched across the two modalities. Visual matrices showed all of the to-be-remembered locations simultaneously, whereas one haptic block was presented at a time in different locations and an interference task was done in between presenting each location. Also, as is common in tasks comparing vision with haptics, the haptic stimuli were presented for much longer to try to produce similar levels of performance. Participants had 5 s to encode the entire visual matrix independent of the number of items, whereas they had 5 s to explore each item in the haptic task. Thus, the haptic task produced a much greater load on working memory than the visual task. More interesting was the comparison between the effects of visual versus haptic interference on visual versus haptic span. The retention interval between encoding and retrieval of the spatial information could be filled by an interference task that was either haptic (rotating a block) or visual (deciding whether two arrows pointed to the same place). Performance was worse when the secondary interference task had the same modality as the primary spatial span task (e.g., when haptic interference occurred during the haptic span task), which suggests that distinct systems were responsible for maintaining visual and haptic spatial information.

In a similar spatial memory task, Sebastián et al. (2008) presented visual and haptic 3 × 3 matrices. There were two targets and one distracter in each matrix. Participants had to remember the target positions and ignore the distracter. A 6-s retention interval was filled with one of four interference tasks: haptic spatial (using the nondominant hand to explore an empty matrix), visual spatial (tracking a continuously moving dot on the screen), verbal (articulatory suppression), or a visual static control (looking at a fixation cross). Given the spatial nature of the primary task, it was perhaps unsurprising that only the two spatial tasks impaired performance. More interestingly, the spatial interference was modality specific, replicating the finding that Paz et al. (2007) reported. When the primary task was haptic spatial recall, only the haptic spatial interference task significantly impaired performance. In contrast, when the primary task was visual spatial recall, only the visual spatial interference task significantly impaired performance. Sebastián et al. suggested that their results indicated a modality-specific component to spatial encoding across vision and haptics. However, the trend was for both visual and haptic spatial interference tasks to impair recall on both the visual and the haptic primary matrix tasks, so they did not produce wholly distinct patterns of interference. A further problem in interpreting their results is that the two spatial interference tasks were both different from each other and did not exclusively tap spatial processing. For example, tracking a moving dot and exploring an empty matrix by touch involve different attentional and motor control processes.

Finally, Cohen et al. (2010) tested working memory by measuring people's visual and haptic span for immediate serial recall of letters. They reported that congenitally blind participants' haptic span for Braille letters was as good as sighted participants' visual span for visually presented letters. This was the case both with and without articulatory suppression (repeatedly saying "bla"). Thus, the capacity of blind people's short-term tactile memory was equal to sighted people's visual memory, at least for these stimuli. In a second experiment, participants who were blind or had only residual vision performed a secondary interference task in addition to the primary haptic span task with Braille letters. Interference was either verbal (mental arithmetic) or haptic-spatial (feeling a matrix of blocks and then being instructed to imagine moving the blocks, and then reporting the final block configuration). Performing these tasks concurrently with the primary task reduced span for both interference conditions, relative to a no-interference control condition. Greatest disruption (floor performance) followed spatial interference. However, the spatial interference task was extremely demanding and it drew on a wide range of different processes (imagery, motor, haptic, verbal, and spatial). It is thus not clear what aspect of this task resulted in the poor span performance.

In summary, these studies by Cohen et al. (2010), Paz et al. (2007), and Sebastián et al. (2008) suggest that haptic interference and spatial interference reduce haptic span relative to no interference. In addition, spatial interference may be modality-specific, with haptic span being disrupted more by haptic-spatial interference than by visuospatial interference.

We next consider the effects of interference on haptic perception tasks. Ittyerah and Marks (2007) investigated unimodal and cross-modal haptic (H) and visual (V) discrimination of curvature. They used five different interference tasks during a 30-s retention interval. Visuospatial-motor interference (placing a set of paper clips at regular, experimenter-specified intervals) and motor interference (using both hands to move books between two piles without vision) disrupted HH and HV discrimination relative to both a no-interference control condition and to verbal interference (counting aloud). Surprisingly, continued exploration of the first stimulus during the retention period did not improve performance relative to the no-interference control although it eliminated the need for rehearsal. No significant differences were found among the five interference conditions for VV and VH discrimination, and there was only a marginal effect of interference, with visuospatial-motor and motor interference generally reducing accuracy relative to the no-interference control, consistent with the pattern for the HH and HV tasks. Fewer participants were tested on the VV and VH tasks than the HH and HV tasks and different (though overlapping) sets of curvature discrimination stimuli were used in these tasks. This means that there may simply have been less power to detect effects in the VV and VH tasks, particularly because performance was the highest possible in a number of conditions, which makes cross-condition comparisons difficult.

Gentaz and Hatwell (1999) tested the influence of interference during a 30-s retention interval for an orientation reproduction task with a rod. A no-interference control condition was compared with a challenging verbal interference task (naming the letters of the alphabet in reverse order) and a haptic interference task (moving a finger between two points along a raised path). Performance in the two interference conditions was similar and was worse than the no-interference condition.

Finally, Seemüller, Fiehler, and Rösler (2011) used a delayed match to sample test with simple two-line angle stimuli that were presented either visually or for passive kinesthetic exploration (the right hand held a stylus that was programmed to move along a trajectory). The interference task involved determining the orientation of an ellipse that was presented visually or by passive kinesthetic exploration as for the primary task. Interference during the retention interval reduced accuracy on the primary matching task relative to a no-interference control condition. Seemüller et al. further argued that this interference was modulated by modality. However, this interaction was not significant in their main analysis. It was only significant in a difference analysis, and there it amounted to only a 2% extra decrease in accuracy for visuospatial relative to kinesthetic interference when matching visually encoded stimuli and a similar extra cost for kinesthetic compared with visuospatial interference when matching kinesthetically encoded stimuli.

These three studies, which tested haptic perception of curvature (Ittyerah & Marks, 2007), orientation (Gentaz & Hatwell, 1999), and kinesthetic perception of angle (Seemüller et al., 2011) as the primary tasks, found discrepant results. Relative to no interference, both visuospatial and motor interference disrupted curvature perception but verbal interference had no effect; verbal and haptic interference both disrupted orientation reproduction, and visual and passive kinesthetic interference both disrupted angle perception. Furthermore, the pattern of results in all three studies was more complex than the summary presented here. It seems that no clear generalizations can be drawn from these findings.

Finally, we consider the effect of interference tasks on haptic shape recognition tasks. Using unfamiliar plastic 3D shapes, Millar (1972) reported that neither verbal interference (repeating digit strings) nor visual interference (viewing colored pictures) during a 9-s retention interval affected haptic shape recognition by children. Subsequently, Millar (1974) compared old/new recognition of unfamiliar 3D shapes by blind and sighted children with interference tasks used during a retention interval of up to 30 s. Both blind and sighted children responded more slowly after verbal interference (counting backward in threes) or haptic/motor interference (stacking 3D shapes) relative to either a no-interference control condition or to a rehearsal task involving tracing with a finger the to-be-remembered shapes on a surface. However, no interference effects were obtained in a second experiment that tested only sighted children. This largely replicated the first experiment but there were fewer repetitions (eight rather than 32) of the shapes used in the primary task. There, there was only an effect of the retention period with faster and more accurate recognition for shorter durations.

In more recent work, Holtby and D'Angiulli (2012) reported that haptic perception of raised line drawings was impaired by both verbal interference (articulatory suppression) and visual interference (DVN) at encoding. They suggested that haptic information was recoded into verbal and visuospatial representations. However, people's ability to recognize raised line drawings is much worse than their recognition of 3D objects (Lawson & Bracken, 2011; Wijntjes, van Lienen, Verstijnen, & Kappers, 2008), probably in large part because of the lack of depth information for such stimuli (Lawson & Bracken, 2011). As such, the recognition of raised line drawings may be unusually reliant on visual recoding (for example, by imagining how the stimulus would look, as proposed by the image mediation account) (see Lederman & Klatzky, 1990; Lederman et al., 1990). Moreover Holtby and D'Angiulli's (2012) task involved the experimenter guiding the participants' finger along the raised line drawings at a constant pace. Such passive encoding is different from our everyday active perception of shape by our hands, which may have further encouraged the use of unusual recoding strategies in this task.

More generally, few previous studies on memory for touch adapted working memory paradigms to take account of the specific strengths and weaknesses of our sense of touch and spatiotemporal differences in stimulus exploration by touch. In particular, studies of haptic shape and object perception rarely permitted the hand to freely explore real everyday 3D objects. An exception is Lacey and Campbell (2006), who investigated the accuracy of cross-modal (haptic-visual and visual-haptic) old/new recognition of familiar and unfamiliar objects in two interference experiments. Participants either touched with their dominant hand or saw a set of objects and then they saw or touched the same objects plus a set of distracters and tried to decide which objects were new. They did a simultaneous interference task at either the encoding stage or the retrieval (recognition) stage. The interference tasks were described as haptic (manipulating an object with their nondominant hand), visual (looking at DVN), or verbal (hearing irrelevant speech through headphones). Interference at encoding did not affect familiar object recognition, although accuracy was over 95%, so ceiling effects may have made it difficult to distinguish between the conditions. Relative to a no-interference control condition, unfamiliar object recognition was disrupted by both verbal and visual interference at encoding but not by haptic interference. There was no main effect of interference at retrieval but performance was accurate and over 95% for familiar objects, so again ceiling effects may have limited the sensitivity to detect interference effects. However, notwithstanding this issue, the disruptive effect of verbal interference for the haptic recognition of unfamiliar objects suggests that verbal strategies for encoding haptically presented stimuli are not restricted to nameable objects and might include subvocal description for unfamiliar objects.

These final four studies used interference tasks to probe shape and object recognition by touch. They employed a wide variety of stimuli and of primary and interference tasks. Nevertheless, their results were consistent in showing widespread interference effects. Specifically, haptic/motor, verbal, and visual interference all disrupted performance relative to a no-interference control condition. In some cases, though, no interference effects were found: for example, when stimuli were repeated fewer times (Millar, 1974).

DRAWING CONCLUSIONS FROM STUDIES OF MEMORY FOR TOUCH USING INTERFERENCE TASKS

We have reviewed a series of 13 studies on memory for touch that used one or more interference tasks. To summarize their findings, studies of memory for tactile location suggested that tactile and verbal interference disrupted performance relative to no interference. Studies of haptic span suggested that both haptic-spatial and visuospatial interference reduced span relative to no interference. Furthermore, this interference was modality-specific, with haptic spans reduced more by haptic-spatial than by visuospatial interference, and vice versa for visual spans. Visuospatial and motor interference both disrupted haptic curvature perception but verbal interference had no effect, whereas verbal and haptic interference both disrupted orientation reproduction, and visuospatial and kinesthetic interference both disrupted kinesthetic angle perception. Finally, studies of haptic shape and object recognition indicated that haptic/motor, verbal, and visual interference all could disrupt performance.

Overall, these results indicate that a range of interference tasks can disrupt memory for touch but that tasks with a spatial element may be particularly effective. However, when interference is found, this may sometimes simply reflect the added difficulty of doing two tasks together (i.e., the interference is not a consequence of targeting a specific component process in the primary task). Similarly, when interference is absent, it could reflect the use of an insufficiently demanding interference task. Studies testing multiple secondary interference tasks have not compared directly the ease of performing each task and the tasks used often seem poorly matched for difficulty. This issue alone could account for the varied effects of the tasks and the problem of drawing clear-cut conclusions from the results of these studies. We now turn to our own data and present two interference studies that investigated haptic object memory. Both studies allowed free manual exploration of complex 3D objects that were moderately or highly familiar. Thus, we used both stimuli and a task well-suited to this modality.

EXPERIMENT 1

In our first study we investigated the effects of four interference conditions (motor, haptic, spatial, and verbal) plus a control no-interference condition on an old/new object recognition task with objects of high and low familiarity. The interference tasks occurred during object encoding to try to elucidate the nature of the encoding strategies used in haptic object recognition. For example, verbal interference would be expected to disrupt verbal encoding strategies such as giving basic-level labels to familiar objects or sub-vocally describing unfamiliar objects (see Lacey & Campbell, 2006).

Method

Participants There were 150 participants. Half were presented with more familiar objects and half with less familiar objects. Within each of these two groups, 15 participants were allocated to each of five interference conditions (motor, haptic, spatial, verbal, and no interference). Participants were students and former students at the University of Minho; they participated for course credit or inclusion in a prize draw with 30 prizes of 10-Euro vouchers.

Materials and Procedure Objects were small enough to be explored with one hand and were presented inside a wooden box to prevent them from being seen. The box was divided in half with the participant's right and left hands going into each half. To prevent participants from hearing noises from the objects as they touched them, participants wore headphones that produced white noise. A computer screen was placed on top of the box and was used to present the stimuli for the verbal and spatial interference tasks. Haptic encoding for the primary task consisted of 3 s of free exploration of each of 50 objects using the nondominant hand. The nondominant hand was used because during piloting, participants stated a preference for using the dominant hand to do the haptic interference task, and Craddock and Lawson (2009a) reported no difference in performance between the dominant and nondominant hand for haptic object recognition. Sound cues were provided through the headphones to start and end object exploration. In the test, each participant felt 25 of the old items that had been presented at encoding and a further 25 new items in random order. They were told to make an old/new decision as quickly and accurately as possible.

All 75 objects presented to a given participant were randomly selected from either a pool of 92 highly familiar, real objects (such as a spoon and a pair of scissors) or a pool of 83 less familiar objects (such as a toy tractor or a plastic chili). The objects were rated for familiarity using a five-point Likert scale (1 = used less than once a year; 5 = used almost every day or more). The set of 92 highly familiar objects had mean ratings of 3.5 (standard deviation (SD) = 0.5) and 83% (SD = 3%) were correctly identified. The set of 83 less familiar objects had mean familiarity ratings of 2.5 (SD = 0.6) and 37% (SD = 3%) were correctly identified.

The interference tasks were performed twice by each participant: once in a single task condition (composed of a block of 50 trials in which no objects were presented haptically) and once concurrent with haptic encoding (in which the 50 objects for the primary recognition task were also presented for encoding, one per trial). The single interference task condition was performed before haptic encoding for around half of the participants in each group; it was done after the old/new recognition task for the remaining participants.

There were five interference groups. One did the *control (no-interference)* condition and another did a *motor interference* condition that required no response. The remaining three groups did *verbal, spatial*, and *haptic* interference tasks, all of which required people to make same/different judgments. Stimuli in the interference tasks were each presented for 3 s and verbal yes/no responses to the verbal, spatial, and haptic tasks were required immediately after each presentation. The participant's dominant hand rested on the inside of the box during encoding, except for the haptic and motor interference groups. The experimenter monitored compliance with the interference task instructions.

The *haptic interference task* involved deciding whether pairs of paper samples (e.g., white, recycled, magazine, newspaper, photo) were the same. Trials were presented pseudo-randomly from a set of 52 same pairs and 58 different pairs. The *motor interference* task required people to perform similar movements as for the haptic interference task and to rub the fingers of the dominant hand from the top to the bottom of the box. However, no paper samples were presented and they were not told to do a task. The *spatial interference* task simultaneously presented two of the 3D abstract shapes used by Shepard and Metzler (1971) on the computer screen. Participants decided whether each pair had the same shape. Same pairs were identical shapes but rotated by 40° in the plane from each other. Different pairs were mirror images of each other that were also rotated 40° in the plane from each other. The stimuli for the *verbal interference* task consisted of pairs of tri-syllabic pseudo-words that people had to read aloud. Participants decided whether each pair had the same syllables. In same pairs, both pseudo-words had the same syllables but in different order (e.g., TA-FA-LE/FA-LE-TA). In different pairs the consonants and vowels were switched across two syllables (e.g., NO-SI-NE/NI-NE-SO). At the beginning of the experiment, the no-interference group did six practice trials of the primary haptic task. The interference groups performed six practice trials of their interference task alone and then six practice trials of the interference task plus the haptic task.

Results

Analyses were conducted on corrected hit rates (hits minus false alarms) for the primary old/new haptic recognition task. An analysis of variance (ANOVA) was conducted with two between-subjects factors of object familiarity (high or low) and interference task at encoding (none, motor, haptic, spatial, or verbal). There was a significant effect of object familiarity, $F(1, 140) = 90.34$, $p < .001$, partial $\eta 2 = 0.39$. As expected recognition of highly familiar objects (0.73) was better than that of less familiar objects (0.46). There was also a significant effect of interference task, $F(4, 140) = 16.23$, $p < .001$, partial $\eta 2 = 0.32$. Finally, these two main effects were modulated by a significant interaction between familiarity and interference task, $F(4, 140) = 3.04$, $p = .02$, partial $\eta 2 = 0.08$) (see Figure 1), showing that the effects of the interference tasks depended on the type of objects presented. Post hoc Newman–Keuls analyses revealed that for the more familiar objects there was no significant difference among the no-interference (0.85), motor interference (0.86), verbal interference (0.72), and spatial interference (0.72) groups. However, all four groups were more accurate than the haptic interference group (0.50). In contrast, for the less familiar objects, the no-interference group (0.67) was more accurate than all four interference groups. The only significant difference among the motor interference (0.51), spatial interference (0.41), haptic interference (0.37), and verbal interference (0.32), groups was greater accuracy with motor interference than verbal interference.

Discussion

In Experiment 1 the disruptive effects of the different interference tasks on the encoding of haptic objects were modulated by object familiarity. Recognition memory for all objects was clearly disrupted by haptic interference at encoding, relative to a no-interference control task. In contrast, spatial, verbal, and motor interference all reduced accuracy relative to no interference for less familiar but not for highly familiar objects. This interaction may have been driven by task difficulty, with spatial, verbal, and motor interference having an influence only when recognition was particularly hard, whereas haptic interference was detrimental irrespective of task difficulty and despite different hands performing the interference and the primary tasks. This, in turn, suggests that haptic processes may have a more fundamental, unavoidable role during haptic encoding than spatial, verbal, and motor processes. In contrast, the disruptive effects of spatial, verbal, and motor interference under demanding dual-task conditions may result from competition for central resources under these circumstances.

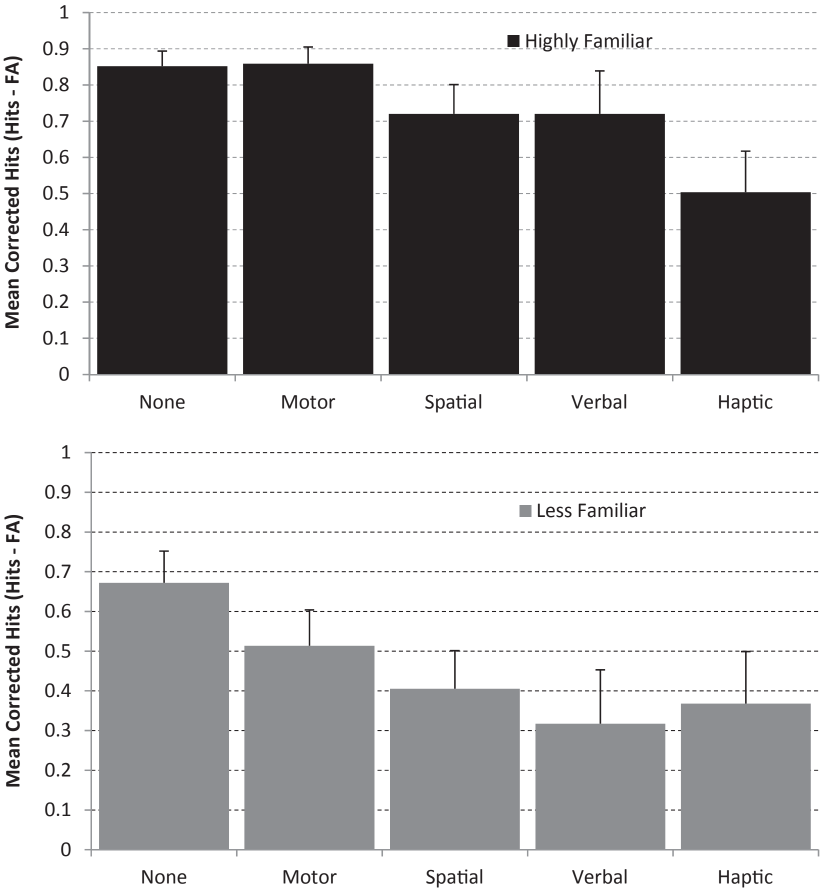

FIGURE 1 Corrected hits (hits minus false alarms) in Experiment 1 for the primary haptic recognition task for the no-interference condition and the four interference conditions (motor, haptic, spatial, and verbal), for the more (top) and less (bottom) familiar object sets separately. Error bars show 95% confidence intervals.

EXPERIMENT 2

In this study we compared the effect of three interference tasks (verbal, spatial, and motor) relative to a no-interference control condition using an object-matching task. Unusually for interference studies, these four conditions were manipulated within-subjects, removing inter-subject variability. The objects used were plastic scale models of familiar, nameable objects; the primary task of sequential matching has been used previously with these stimuli (Lawson, 2009). Unlike Experiment 1, the interference tasks were performed during the retention period between presenting the first and second object on each matching trial. Targeting interference at retention minimized the likelihood of peripheral problems in combining the primary, matching and secondary, interference tasks, which could disrupt encoding or retrieval processes. This study attempted to determine the nature of the perceptual representations involved during the rehearsal and maintenance of information required for haptic object recognition.

Method

Participants There were 32 participants who were students at the University of Liverpool. They participated for course credit or without reward.

Materials and Procedure Sixteen pairs of plastic 3D models of familiar objects such as tables and dogs were presented sequentially to participants. The objects were approximately hand-sized. Lawson (2009) provides further details about their production. Half of the trials were match trials in which the same object was presented twice (e.g., chair then chair). On the remaining mismatch trials the second object had a shape similar to the first but it could normally be distinguished haptically from it. The difficulty of shape discrimination was the medium context condition tested in Experiment 2 of Lawson (2009) and the two objects presented on a mismatch trial would usually be given a different basic-level name (see Experiment 1 in Lawson, 2009); examples included bath–sink, cup–jug and lizard–frog. Thus on mismatch trials, participants never had to distinguish between two exemplars of the same category (e.g., two different chairs) although the two objects always had related shapes. Participants made a rapid decision as to whether the two objects presented on a trial were the same or different. They responded with the left hand by making a speeded key press using a button box.

The 64 experimental trials were divided into four blocks of 16 trials with one block for each of the four interference conditions. The order of the four interference conditions was counterbalanced using a Latin square design across the participants. The order of the items was fixed. One order was used for half of the participants in each subgroup and the reverse order was used for the remaining participants. Each pair of objects was presented once in every block. Over the 64 trials, each pair was presented twice on match trials and twice on mismatch trials, with the two objects in a pair presented in a different order on each mismatch trial (so the four trials for the pig–dog pair were pig–pig, dog–dog, pig–dog. and dog–pig). The experimental trials were preceded by eight practice trials that had the same interference task as the first experimental trial. The experimenter explained each interference task immediately before each sub-block of trials that used that task.

On each trial the experimenter placed the first object behind an opaque glass screen so it was not visible to the participant then triggered the computer to say "go now." The participant then had 5 s to feel the first object with their right hand. A ″stop now" cue was then played to them. This indicated that they had to stop feeling the first object and to start doing the interference task. This was done for 7 s in the retention interval between feeling the two objects. Another "go now" signal then indicated that they could stop the interference task and start to feel the second object which was presented in the same location as the first object until participants responded.

All participants completed four interference conditions: a control (*no-interference*) task and three interference tasks. In the *control task* participants waited quietly in the 7-s retention interval. In the *verbal interference task* participants were told a letter and were asked to name aloud as many different words as possible beginning with this letter during the retention period. A new letter was presented on each trial. This task should have disrupted any sub-vocal rehearsal strategy such as remembering the name of the first object. If participants simply retrieved the name of the first object from memory and rehearsed it, this interference task is a reasonable match for the underlying cognitive process because it required participants to retrieve single words from memory. In the *spatial interference task* participants were told a letter and had to visualize it as a giant capital letter and report aloud in which direction they would have to turn if they were walking clockwise around it, starting from the bottom left corner. For example, for T they should have responded "left," ″right," "right," "left," "right." They were given further letters if they completed the first letter during the retention interval. Only straight-edged letters suitable for the task were used. In the *motor interference task* participants used the left hand to move jigsaw puzzle pieces as quickly as possible, one at a time, between two adjacent bowls. The spatial and motor interference tasks were designed to try to disrupt the maintenance of any spatial or motor representations of the first object. However, all three interference tasks drew on multiple processes; for example, the spatial task included verbal responses whereas the motor task had a spatial component.

Results

The analyses were conducted on mean correct response times (RTs) and percentage correct on the haptic matching task. Response times less than 1 s or greater than 10 s were removed as outliers (less than 1% of trials). An ANOVA was conducted with two within-subjects factors of matching (same or different) and interference task during the retention period (none, verbal, spatial, or motor). RTs were similar across the control task (4.3 s) and the three interference tasks (4.0 s for verbal, 4.0 s for spatial, and 4.1 s for motor) and there were no significant effects on the RT analysis. In the error analysis, there was a significant effect of matching, $F(1, 31) = 9.89$, $p = .004$, partial $\eta 2 = 0.24$, with greater accuracy on same trials (79.8%) than on different trials (70.6%). There was also a significant effect of interference task, $F(3, 93) = 10.89$, $p < .001$, partial $\eta 2 = 0.26$. There was no interaction between these two factors, $F(3, 93) = 1.83$, $p > .1$, partial $\eta 2 = 0.06$. Post hoc Newman–Keuls analyses revealed that the accuracy of haptic matching was reduced by spatial interference (66.2%) relative to the other three conditions, and that there was no difference between the no-interference (80.9%), verbal interference (79.1%), and motor interference (74.6%) conditions.

Discussion

Experiment 2 investigated the nature of the processes involved in rehearsing and maintaining haptically acquired object representations. The results were straightforward: spatial interference disrupted accuracy on object matching relative to a no-interference control condition whereas verbal and motor interference did not. In the secondary spatial interference task people had to imagine a capital letter and say which directions they would have to turn if they were to walk around it. This task involved both visual imagery and spatial transformations. In contrast, simply moving the hands during the motor interference task did not disrupt performance on the primary, matching task, whereas the spatial interference condition, which did disrupt matching, did not require movement. Although the objects used were generally familiar, nameable shapes (Lawson, 2009), verbal interference did not disrupt performance relative to the control no-interference task. This may have been because the primary matching task involved difficult shape discrimination (overall accuracy was 75%). The similarity of the two objects presented on different trials (e.g., a chair and then a bench; or a frog and then a lizard) meant that participants had to maintain detailed shape information to perform well. Merely remembering a name for the first object would often not have been sufficient to support accurate performance because these objects could not be named reliably and the same name would often have been given to different shaped objects (see Experiment 1 of Lawson, 2009).

Together, these results suggest that people did not retain their memory of the first object using motor or verbal strategies but that instead, spatial coding was important to the maintenance of accurate haptic shape representations; i.e., people retained and/or rehearsed spatial rather than verbal or motor representations. However, it is not possible to exclude an alternative hypothesis that the spatial interference task was simply harder than the other interference tasks and that this, in turn, resulted in less attention or processing resources being available for the primary matching task. This seems a reasonable critique of the no-interference and motor interference conditions. However, the word generation task used for verbal interference is demanding and is thought to tap executive functioning as well as verbal processes (Barry, Bates, & Labouvie, 2008).

The spatial tasks used in Experiments 1 and 2 required visual processing and/or visual imagery. The results from haptic span tasks reported by Paz et al. (2007) and Sebastián et al. (2008) and reviewed above showed that spatial interference was modality-specific. This suggests that even stronger spatial interference effects could have been obtained in the current studies if haptic rather than visual spatial tasks had been used. In future research it will be important to compare visual and haptic object recognition directly as primary tasks while using matched visual-spatial and haptic-spatial interference tasks to investigate whether modality-specific spatial interference also occurs for object recognition.

GENERAL DISCUSSION

There has been considerable progress in our understanding of haptic and tactile memory, as reviewed above. However, much of the research on memory for touch has presented simple, abstract stimuli and involved passive touch. These conditions are not optimal for this modality, so it is important to expand research on memory for touch to evaluate conditions more similar to those we experience in our everyday life. Tasks better suited to evaluating the strengths of touch perception allow unconstrained, active exploration and present 3D objects with rich information (for example, about material, weight, and size) in contrast to, for example, single finger exploration of 2D raised line drawings (e.g., Holtby & D'Angiulli, 2012; Lawson & Bracken, 2011).

We have focused on assessing studies of memory for touch that used interference or dual-task methodologies. Here, the findings are not wholly consistent. To illustrate this, consider four experiments which we have conducted, two of which were previously published (Lacey & Campbell, 2006) and two new studies that we report here. These experiments share similar methodologies. All four investigated the effects of interference on haptic memory in object processing tasks, with all four comparing a no-interference control condition with three to four different interference tasks. They all included verbal interference and at least two included haptic, visual, motor, and spatial interference conditions. Similar primary tasks (object matching and old/new recognition) and stimuli (complex, 3D objects varying in familiarity) were also used. Despite these commonalities across the four experiments, the results varied. Lacey and Campbell (2006) reported that familiar object recognition was not influenced by interference at encoding (although this may have been due to ceiling effects). In contrast, unfamiliar object recognition was disrupted by verbal interference and by visual interference at encoding, but not by haptic interference. Interference at retrieval had no main effect on accuracy. Experiment 1 here found that for the more familiar objects only haptic interference impaired performance, whereas for the less familiar objects all four interference tasks impaired performance. Finally, Experiment 2 described here found that only spatial interference disrupted performance, with no cost of motor or verbal interference.

These differences could result from variation in the point at which interference was applied, which ranged from encoding to retention to retrieval across the experiments. It could also be because Lacey and Campbell tested cross-modal haptic/visual recognition whereas Experiments 1 and 2 tested unimodal haptic recognition.

In addition, there was considerable variation in the tasks used to apply interference. For example, although articulatory suppression is generally used in memory research to produce verbal interference by preventing verbal rehearsal, none of these studies used it. Instead, Lacey and Campbell had participants passively listen to speech, Experiment 1 used a difficult non-word discrimination task, and Experiment 2 had participants generate words beginning with a specific letter. These three tasks varied in task difficulty and in the specific components of verbal processing that each tapped.

We raise these points to illustrate that if clear and wide-ranging conclusions are to be drawn from haptic interference studies, they need to use sets of standard secondary interference tasks and/or theoretically well-motivated tasks (see Chan & Newell, 2008) that precisely tap distinct cognitive processes. Furthermore, task difficulty should be matched across the different interference tasks and performance on the interference tasks should be monitored. None of our own experiments investigating haptic interference effects or those reported in the other 12 published studies investigating tactile and haptic interference studies that we reviewed above achieved all of these demanding conditions. The strongest design would include multiple primary tasks as well as multiple interference tasks, but this has rarely been done.

Notwithstanding these challenges to interpreting results from haptic interference tasks, we believe that a number of interesting conclusions can be made about the role of movement and verbal, haptic, and spatial processes in representing stimuli presented to touch. From the earliest experiments on touch, researchers have highlighted the role of movement in recognizing and identifying stimuli (Gibson, 1966; Kaas, Stoeckel, & Goebel, 2008; Nefs, Kappers, & Koenderink, 2001; Millar, 1999). For example, Millar (1999) suggested that a movement loop could be used as a rehearsal system for touch, similar to the phonological loop proposed for rehearsing verbal material (see Baddeley, 2000). This system could mentally rehearse executed movements to maintain a dynamic representation of haptically encoded stimuli and of exploration patterns. There is clear evidence that we encode certain stimulus properties such as the orientation in depth of an object relative to our own body (Craddock & Lawson, 2008; Ernst et al., 2007; Lawson, 2009, 2011; Newell et al., 2001). This indicates that we maintain some identity-irrelevant information about how object information was encoded (such as its position relative to ourselves), so there is no a priori reason to assume that motor processes are not also encoded. Nevertheless, the results from both Experiments 1 and 2 here and from the object manipulation condition of Lacey and Campbell (2006) did not support this proposal that we maintain motor representations. Motor interference tasks did not disrupt haptic object processing, with the exception of recognizing less familiar objects in Experiment 1. Further evidence consistent with this comes from Cecchetto and Lawson (2015). We recently found that producing an unseen sketch of a raised line drawing while it was being explored haptically did not reduce the accuracy of recognizing the drawing relative to a no-sketch control condition.

In contrast to this lack of evidence for the importance of motor processes during the acquisition and storage of information presented to the hands, haptic and spatial processes both appear to be important based on the deleterious effects of haptic and spatial interference (see Experiments 1 and 2 here; also Cohen et al., 2010; Gentaz & Hatwell, 1999; Ittyerah & Marks, 2007; Millar, 1974; Paz et al., 2007; Sebastián et al., 2008). Although Lacey and Campbell (2006) reported no effect of haptic interference, their interference task (manipulating an object in the non-encoding hand) is probably better described as a motor interference task because no response was required. The conclusion that haptic object memory representations have a spatial dimension consistent with the 3D structure of the stimuli converges with evidence from tactile working memory studies (e.g., Harris, Harris, & Diamond, 2001; Katus, Andersen, & Müller, 2012).

Finally, there is evidence that verbal and visual processes are also involved in acquiring and storing information perceived by touch, at least during the haptic encoding of less familiar objects (see Experiment 1 here; Experiment 1 of Lacey & Campbell, 2006; and Cohen et al., 2010; Gentaz & Hatwell, 1999; Holtby & D'Angiulli, 2012; Millar, 1974). However, as discussed above, many other studies have failed to detect disruptive effects of verbal or visual interference tasks, and so it remains unclear what factors determine whether these interference effects are observed.

The apparent diversity of effects of interference tasks on haptic object processing may be reconciled by assuming that alternative strategies may be used during the encoding and maintenance of haptic representations with the choice of strategies varying depending on the task used, the stimuli, and the individual. One strategy is to encode a haptic representation; alternative or additional strategies include the use of covert naming and verbal descriptions, as well as employing visuospatial and haptic-spatial imagery. These various processes may lead to distinct representations of the input being produced in parallel, but such representations would be short-lived. Their role may be to help to establish a single, more durable, modality-independent spatial representation that can then be maintained in short-term memory. This representation could subsequently be matched to both visual and haptic inputs and it could be transferred to a permanent memory store.

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