Cognition 128 (2013) 363–379

Contents lists available at SciVerse ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

Ambient visual information confers a context-specific, long-term benefit on memory for haptic scenes

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ARTICLE INFO

Article history:
Received 5 April 2012
Revised 25 April 2013
Accepted 30 April 2013
Available online 10 June 2013

Keywords:
Noninformative vision
Haptic memory
Scene recognition
Spatial memory
Reference frames
Multisensory

ABSTRACT

We investigated the effects of indirect, ambient visual information on haptic spatial memory. Using touch only, participants first learned an array of objects arranged in a scene and were subsequently tested on their recognition of that scene which was always hidden from view. During haptic scene exploration, participants could either see the surrounding room or were blindfolded. We found a benefit in haptic memory performance only when ambient visual information was available in the early stages of the task but not when participants were initially blindfolded. Specifically, when ambient visual information was available a benefit on performance was found in a subsequent block of trials during which the participant was blindfolded (Experiment 1), and persisted over a delay of one week (Experiment 2). However, we found that the benefit for ambient visual information did not transfer to a novel environment (Experiment 3). In Experiment 4 we further investigated the nature of the visual information that improved haptic memory and found that geometric information about a surrounding (virtual) room rather than isolated object landmarks, facilitated haptic scene memory. Our results suggest that vision improves haptic memory for scenes by providing an environment-centred, allocentric reference frame for representing object location through touch.

1. Introduction

Our ability to visually perceive and represent the spatial layout of objects in memory has received a lot of attention in the literature (for a review see e.g. Burgess, 2008), and more recent studies have investigated spatial perception within other modalities, particularly the tactile (e.g. Kappers, 2004, 2007; Kappers & Koenderink, 1999) and auditory modalities (e.g. Klatzky, Lippa, Loomis, & Golledge, 2003; Zimmer, Lewald, Erb, & Karnath, 2006). Findings from recent studies on cross-modal spatial cognition suggest that there are sufficient functional similarities across the visual and tactile senses to allow for multisensory information to be integrated into a common spatial representation in memory (see Giudice, Klatzky, & Loomis, 2009; Kelly, Avraamides, & Giudice, 2011; Klatzky, Lippa, Loomis, & Golledge, 2002; Loomis, Klatzky, Avraamides, Lippa, & Golledge, 2007) and to allow for equivalent spatial performance across vision and touch in sighted and blind individuals respectively (Giudice, Betty, & Loomis, 2011). Yet, relatively little is understood about how such integration occurs or indeed how these modalities interact for the purpose of multisensory spatial cognition and, more particularly, whether multisensory integration affects the representation of spatial locations of multiple objects.

It is known, for example, that relevant visuo-spatial information can enhance performance when crossmodal events are co-located (Santangelo, Ho, & Spence, 2008) and that visuo-spatial perception and attention can be disrupted when incongruent crossmodal spatial information is provided (see Spence & Driver, 2004 for an overview). Indeed, it is often argued that vision is likely to affect spatial processing in other modalities since it provides the 'gold

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http://dx.doi.org/10.1016/j.cognition.2013.04.011

standard' in spatial precision to which other modalities may refer (Myklebust, 1964; Thinus-Blanc & Gaunet, 1997). This idea is compatible with the suggestion that the brain is 'metamodal' (Lacey, Tal, Amedi, & Sathian, 2009; Pascual-Leone & Hamilton, 2001), in that, brain functions are organised based on the type of computation performed (e.g. spatial perception) rather than on the origin of the sensory input. For example, several studies have suggested that the absence of visual experience during the course of development can be associated with relatively poor spatial abilities in the intact senses (e.g. Pasqualotto, Spiller, Jansari, & Proulx, 2013; Schicke, Demuth, & Röder, 2002). Additionally, others have argued that early visual experience seems to be necessary for both the development of efficient spatial cognition (Byrne & Salter, 1983; Gaunet, Martinez, & Thinus-Blanc, 1997; Herman, Chatman, & Roth, 1983; Pasqualotto & Newell, 2007; Pasqualotto & Proulx, 2012; Postma, Zuidhoek, Noordzij, & Kappers, 2008a; Rieser, Hill, Talor, Bradfield, & Rosen, 1992), and to calibrate spatial precision in other spatial senses (Röder, Kusmierek, Spence, & Schicke, 2007).[1] Since visual information which is directly relevant to a task, can affect spatial processing in other modalities, in the following experiments we investigated whether ambient, or surrounding, visual information, which was not directly related to the task, could affect spatial performance in another modality, namely touch. More specifically, we were interested in investigating whether visual context can affect the representation of scenes of objects encoded through touch, and whether any effect of vision may be long-lasting.

The term "noninformative" visual information has previously been used to refer to visual information that is not directly relevant to the tactile task nor has any predictive value of the nature of the tactile stimulation. Despite being noninformative such visual information has nevertheless been shown to provide a benefit to the perception of tactile stimulation, including reducing the 2-pin tactile threshold (Honoré, Bourdeaud'hui, & Sparrow, 1989; Kennett, Taylor-Clarke, & Haggard, 2001) and tactile orientation discrimination (Taylor-Clarke, Kennett, & Haggard, 2004). Furthermore, tactile discrimination of stimuli on the body was also improved by viewing the shadow of the stimulated, but not the unstimulated, hand (Galfano & Pavani, 2005; Pavani & Galfano, 2007). Thus, the above studies provide strong evidence that noninformative vision can improve the discrimination of passively presented tactile stimulation to the body.

Other studies on tactile spatial perception, involving active exploration (i.e. haptic) of stimuli external to the body, have also reported evidence that perceptual performance is improved by noninformative vision (e.g. Newport, Rabb, & Jackson, 2002; Postma, Zuidhoek, Kappers, & Noordzij, 2006; Volcic, van Rheede, Postma, & Kappers, 2008; Zuidhoek, Visser, Bredero, & Postma, 2004). In general, these studies involve a haptic orientation matching task in which the participant has to change the orientation of a stimulus bar, by up to 180° in the horizontal plane, to match the orientation of a reference bar (see e.g. Kappers, 2002; Kappers & Koenderink, 1999 for the original design). Newport et al. (2002) found that when naïve participants could view their surroundings, but not the tactile stimuli (i.e. so called "noninformative vision"), performance in this haptic matching task was significantly improved relative to when participants were blindfolded. Moreover, performance was particularly improved when participants were encouraged to use a more allocentric frame of reference during tactile exploration of the stimuli. Thus, Newport et al. demonstrated that the presence of visual information, although noninformative to the task, was sufficient to improve the spatial perception (i.e. orientation) of tactile information (see also Postma, Zuidhoek, Noordzij, & Kappers, 2008b).

To our knowledge, the role of ambient (or non informative) vision on haptic spatial memory has not been investigated. Recent reports have suggested that the provision of a visual reference frame prior to learning an object scene through vision can influence the subsequent representation of a scene encoded either through vision (Kelly & McNamara, 2010) or touch (Kelly & Avraamides, 2011; Kelly et al., 2011). Moreover, these results, together with those of previous studies on object perception (e.g. Newport et al., 2002), provide evidence for a cross-modal transfer or integration of spatial reference frames. However, it remains unknown whether ambient visual information, which is not directly related nor is explicitly embedded into the haptic task, can also improve haptic spatial memory for multiple objects. Thus, one of the aims of the experiments reported here was to assess whether information from the surrounding visual environment affects the spatial representation of scenes of objects acquired through haptics. Based on the studies outlined above (e.g. Newport et al., 2002), we predicted that such visual information would improve haptic spatial memory and we expected to find better haptic recognition when participants could see their surrounding ambient environment (i.e. the laboratory) than when vision was occluded. A second aim was to investigate the time-course of this benefit. Kelly and McNamara (2010) reported that whilst a visual reference frame can affect the nature of the acquired (visual) spatial memory, a subsequent novel reference frame may restructure this spatial knowledge accordingly. This finding suggests that acquired spatial representations are readily adaptable depending on the nature of the available reference frame. However, it is not clear whether such adaptability applies to the representation of scenes across the senses since multiple, sensory-specific reference frames may be available at any one time. Here, we specifically tested whether any benefits of learning a scene through touch while seeing one's surroundings were short-lived and confined to the duration of the task or if there were any long-term benefits. If vision modulates tactile information processing, then it would be expected that haptic information learned in the presence of visual information from the surrounding environment would result in a more robust representation of that information in memory. As such, we might

[1] That is not to say that precise spatial knowledge cannot be acquired by congenitally blind individuals with extensive training in the intact senses: indeed recent studies reporting the acquisition of remarkable spatial abilities in blind individuals, including echolocation and shape recognition through sound, is testament to this (see e.g. Amedi et al., 2007; Thaler, Arnott, & Goodale, 2011).

expect the benefit of ambient visual information on the recognition of the haptic spatial information to be long lasting.

A further aim of the present study was to determine the nature of the benefit of visual information on haptic memory. Newport et al. (2002) reported a benefit for noninformative vision particularly when participants adopted an object-to-environment allocentric reference frame to perceive the tactile stimuli. This suggests that vision benefits haptic spatial processing by providing an allocentric reference frame which is more invariant to incidental changes in object information than a more egocentric reference frame such as one linked to either the hand or the body-axis (see e.g. Ballesteros & Reales, 2004; Volcic & Kappers, 2008). With regard to visual memory, previous studies on the visual recognition of scenes of familiar objects reported evidence that scenes are stored as egocentric representations in memory, such that changes in scene viewpoint incur a cost in recognition performance (Christou & Bülthoff, 1999; Diwadkar & McNamara, 1997; Nakatani, Pollatsek, & Johnson, 2002; Simons & Wang, 1998; Zhao, Zhou, Mou, Hayward, & Owen, 2007). Further studies have reported similar effects of viewpoint changes in haptic scene recognition (Newell, 2004; Newell, Woods, Mernagh, & Bülthoff, 2005) suggesting that spatial information about object locations encoded through haptics is also stored in memory as egocentric representations. However, many studies on visual and haptic spatial processing have argued that allocentric representations are more efficient and result in better memory performance than egocentric representations (see e.g. Gaunet & Rossetti, 2006; Millar & Al-Attar, 2004) although such representations likely need more time to be built up (Zuidhoek, Kappers, van der Lubbe, & Postma, 2003). Thus, the presence of visual cues from the surrounding environment might facilitate the adoption of a more allocentric reference frame in haptics which should, in turn, result in a more robust haptic memory representation across incidental changes such as viewpoint. In other words, if ambient visual information mediates a change in the reference frame used to represent haptic spatial information, we would expect not only a quantitative improvement in overall recognition performance, but also a qualitative change in how haptic scenes are represented and recognised in the presence of ambient visual information.

Based on evidence from visual spatial tasks it is possible to provide some insight into the nature of the haptic reference frame adopted in the presence of visual information by introducing a relatively simple experimental manipulation to the task, namely scene rotation. An effect of scene rotation on performance would be expected if haptic scenes were represented according to either an egocentric or a specific allocentric reference frame. In an allocentric, environment-centred (i.e. object-to-environment or object-to-world) representation, the spatial relations between the objects in the scene relative to the position of fixed features in the environment are explicitly represented in spatial memory (see e.g. Burgess, 2006), and these relations would be disrupted with scene rotation (see e.g. Mou, Fan, McNamara, & Owen, 2007). In contrast, an object-to-object allocentric reference frame would generally not predict an effect of scene rotation on performance since only the spatial relations among the objects within the scene are represented, and these would be unchanged with scene rotation (see Easton & Sholl, 1995; McNamara, 2003; Sholl & Nolin, 1997), unless the objects were arranged such that a salient scene axis emerged which was subsequently difficult to recover following scene rotation (Mou, McNamara, Valiquette, & Rump, 2004). As such, rotating a scene of randomly positioned objects between learning and test can therefore help elucidate which reference frame is adopted when ambient visual information is available by measuring the effect of rotation on haptic performance. However, as noted above, previous studies have suggested that it is unlikely that an egocentric reference frame will be adopted to represent haptic spatial information when ambient visual information is available. Moreover, an allocentric reference frame is thought to facilitate more efficient haptic spatial performance (see e.g. Zuidhoek et al., 2003). Consistent with these findings, we expected better overall haptic recognition performance in our task during conditions when the participant could view their surroundings than those in which they were blindfolded. However, we were unclear as to whether this was facilitated by an object-centred (i.e. view independent) or environment-centred (i.e. view-dependent) allocentric reference frame. The following experiments were designed to investigate these effects further.

2. Experiment 1

In Experiment 1 we investigated whether visual information from the ambient environment[2] had an effect on haptic spatial memory performance. The task consisted of detecting spatial changes in a scene of objects that was previously explored through touch. Two groups of participants performed the task and one of these groups was blindfolded during the first block of trials whereas the other could view their surroundings. In order to investigate any long-term benefits of ambient (noninformative) visual information, participants who were initially deprived of visual input during the task (blindfolded, BF) could view their surroundings in the second block of trials and vice versa. The groups were labelled according to the visual condition encountered in the first block, i.e. noninformative vision (NIV)-first group or blindfolded (BF)-first group. The array of object stimuli was never seen by the participant during the experiment.

Consistent with previous findings (e.g. Newport et al., 2002), we expected overall haptic performance in the noninformative visual condition to be better than that in the blindfolded condition. Moreover, if this advantage for noninformative vision was on perceptual processes only, then we expected this benefit to occur only when visual information was available and not when it was absent during the task, irrespective of when, during the experiment,

[2] For convenience, and to be consistent with the previous literature on such effects on perception, we subsequently refer to this type of ambient visual information as the 'noninformative vision' condition. We use the term 'noninformative' to specifically mean that the visual information has no predictive value on the outcome of the haptic task and could not, on its own, provide a solution to the haptic task.

participants could view their surroundings (such as in the NIV-first group). On the other hand, if noninformative vision affects memory processes involved in the representation of haptic scenes, then we might expect a more long-term advantage for noninformative vision, such that improved haptic performance may continue throughout the task.

We were also interested in investigating how the availability of visual information affected the representation of haptic scenes in memory, i.e. whether the presence of visual information promotes either object-centred or environment-centred allocentric representations of haptic scenes. To distinguish between these two types of representations we included a condition in which the scene was rotated after scene learning, but prior to the recognition task. As described above, we expected environment-centred allocentric representations to be affected by viewpoint changes whereas, in contrast, object-centred allocentric representations should generally not be influenced by changes in scene orientation relative to the observer (c.f. Mou et al., 2004).

2.1. Method

2.1.1. Participants

Forty undergraduate and postgraduate students from the Trinity College, School of Psychology participated in this study for pay or research credits. Twenty-five of these participants were female and fifteen were male. Their ages ranged between 18 and 47. Participants were pseudo-randomly allocated to each of the visual conditions in the first block, in an attempt to match the groups on the sex of participants. As such, the BF-first group included 12 females and 8 males (with a mean age of 24.3 years), while NIV-first group included 13 females and 7 males (with a mean age of 22.1 years). All participants reported normal or corrected-to-normal vision and none reported any tactile impairments. All the studies reported here were approved by the Trinity College School of Psychology Research Ethics Committee. Accordingly, all participants gave informed, written consent prior to the experiment.

2.1.2. Apparatus and stimuli

The entire stimulus set of objects consisted of 15, distinct 3-dimensional wooden shapes of familiar animals: dog, rabbit, cow, cockerel, duck, pig, sheep, cat, bison, farmer, goat, goose, hen, horse and pigeon (see e.g. Newell et al., 2005; Pasqualotto, Finucane, & Newell, 2005). In any one trial, seven objects were randomly chosen from this entire set to create the scene stimulus (as shown in Fig. 1). Each of the object stimuli were 1 cm wide and varied between 6 and 8 cm in height and between 3.5 and 5.5 cm in length. In any one trial, each of the (seven) objects was randomly positioned on a circular platform (diameter of 54 cm). A circular platform was chosen to reduce any effects of a haptic allocentric reference frame on the task. The platform contained 19 sunken positions into which each object stand was firmly inserted such that incidental rotation of the individual objects during haptic exploration could not occur (see Fig. 1). In each trial, each object was randomly rotated relative to the other objects

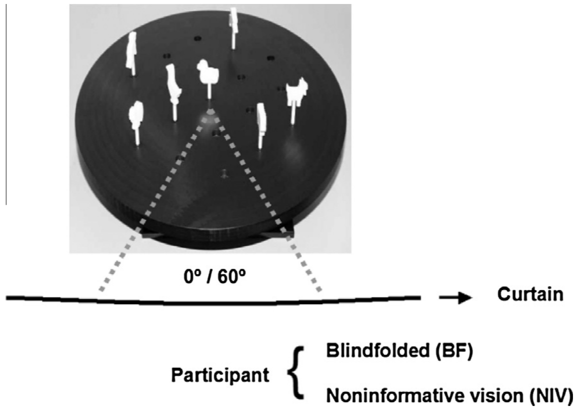

Fig. 1. An image of an example of the object stimuli and apparatus used in all the experiments.

in the scene to avoid any incidental alignment of the objects in the scene. The minimum distance between any two positions of the objects on the platform was 7 cm.

The scene platform was placed behind an opaque curtain that measured 60 by 60 cm. The participant sat on a chair that was positioned in front of the occluding curtain so that the objects could be explored by both hands without being viewed. The centre of the platform was always aligned to participant's body midline.

2.1.3. Design

The experiment was based on a three-way, mixed factorial design with block order (NIV-first or BF-first) as a between-subjects factor and both visual condition in each block (NIV or BF) and scene orientation (0° or 60°) as within-subjects factors. The task was based on an old/new recognition paradigm where participants first learned a scene and were subsequently tested on their recognition of the location of the objects in the scene.

For each participant, two different blocks were presented in succession (with a self-timed break between blocks whilst the participant remained seated) and each block comprised 8 trials. Within each block, in half of the trials the scene was rotated by 60° between learning and test and in the other half the orientation of the scene was unchanged relative to the participant. Trials were randomly presented within blocks and across participants. Participants allocated to the NIV-first condition could see their surroundings (i.e. the testing laboratory) but were subsequently blindfolded for the second block. Conversely, the other 20 participants were blindfolded during the first block (BF-first) but could see their surroundings in the second block of trials.

2.1.4. Procedure

The experiment began with two practice trials and feedback was provided on performance in the practice block only. For each trial, the experimenter randomly chose seven objects among the set of 15 and randomly positioned these objects on the platform. The spatial orientation of the objects was randomised across trials. A trial consisted of learning the scene which was subsequently followed by a recognition test. Participants placed both of their hands underneath the curtain to reach the scene of objects and were instructed that they had 60 s to haptically learn the scene and a test of scene recognition would follow. At the end of the 60 s participants were instructed to remove their hands from the object scene. An interstimulus interval (ISI) of 20 s immediately followed, during which (out of sight of the participant) the experimenter swapped the positions of two (randomly selected) of the seven objects in the array (thus, the overall configuration of the objects remained the same throughout the trial). In addition, according to the experimental design, the platform was either rotated by 60° or maintained the same orientation as learning. Participants were informed that scene rotation could occur in some trials, but they were not aware in which trials the scene would be rotated. We masked any potential auditory cues from the motion of the platform that could be used to infer rotation by simulating the motion of the platform even during the 'no rotation' trials.

During the testing phase participants were instructed to identify the two objects that had swapped positions between learning and test. There was no time restriction for responding although after 2 min of unsuccessful exploration the experimenter prompted the participants for an answer (this occurred very rarely). Participants responded by indicating (e.g. pointing directly at or briefly grasping) the two objects they thought had changed position. Performance was recorded in terms of error rates: when neither of the target objects were correctly identified this was recorded as '100%' error; when only one object was recognized it was recorded a '50%' error; and when both objects were correctly identified it was recorded a '0%' error. Feedback was provided on overall performance at the end of the experiment only. The experiment lasted about 50 min for each participant.

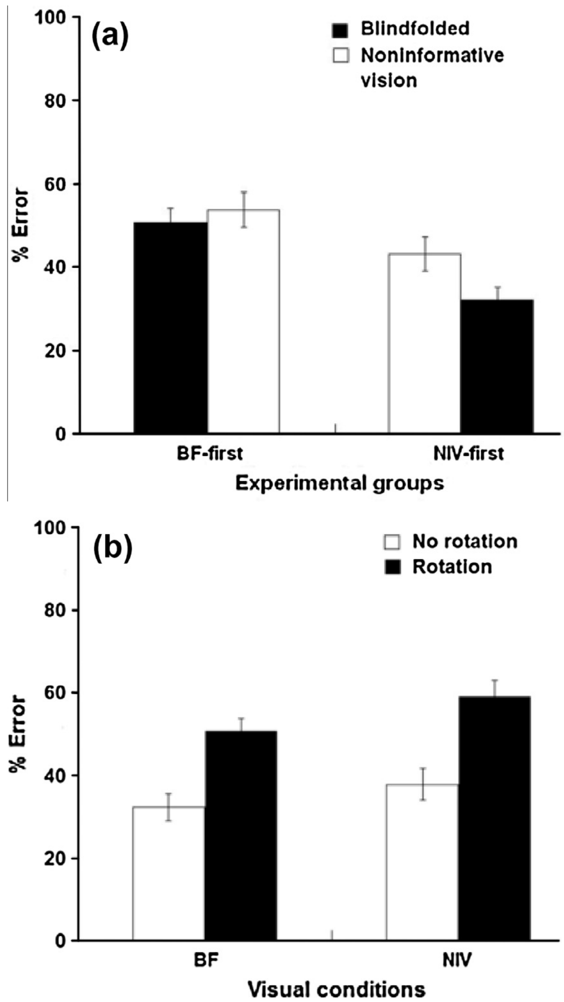

Fig. 2. (a) Graph showing the mean percentage errors across the visual conditions in Experiment 1 with the data collapsed for the condition 'scene rotation' (see the text for details). (b) Graph showing effect of scene rotation across the visual conditions. The error bars represent ±1 standard error of the mean.

2.2. Results

Performance in each condition was above chance level (which was calculated[3] as (23.81% for correct responses or 76.19% for errors). We conducted a three-way mixed ANOVA on the mean percentage errors across participants with block order group (BF-first of NIV-first) as a between-subjects factor, visual condition in each block (NIV or BF) and scene orientation (0° or 60°) as within-subjects factors. We found a main effect of block order [$F(1,38) = 9.52$, $p < 0.05$] with more errors committed by the BF-first group. There was no main effect of visual condition [$F(1,38) = 2.45$, $p > 0.05$]. Although there was a trend towards fewer errors committed in the BF than the NIV conditions overall (i.e. see Fig. 2a), this failed to reach significance. There was a main effect of scene orientation [$F(1,38) = 56.49$, $p < 0.001$] indicating that more errors were committed when the platform was rotated (the mean percentage errors for 0° rotation was 35.0 and for 60° rotation was 54.8) (see Fig. 2b). A significant interaction between block order and visual condition was found [$F(3,36) = 4.99$, $p < 0.05$] which is plotted in Fig. 2a. All other interactions failed to reach significance.

We used a post-hoc Tukey HSD analysis on the interaction between block order and visual condition which revealed that haptic recognition performance did not improve from the first (BF) to the second (NIV) block for the BF-first group [$p > 0.05$], whereas it significantly improved from the first (NIV) to the second (BF) block for the NIV-first group [$p < 0.05$]. Performance for the NIV-first group in the second block (BF) was significantly better than performance in any other condition [$p < 0.05$]. Although performance in the first block performed by each group was worse for the BF-first than the NIV-first group (i.e. the BF and NIV blocks respectively, see Fig. 2a), this difference failed to reach significance [$p = 0.23$]. There were no other significant differences observed.

[3] Using the formula $(2/7 * 5/6 + 5/7 * 2/6)/2 = 23.81$.

2.3. Discussion

The results suggest that, contrary to our expectation based on previous studies, we found no overall benefit on performance when visual information was immediately available relative to the blindfold condition. In other words, noninformative vision had no immediate benefit on haptic recognition performance. Instead, when noninformative visual information was initially available, this information subsequently improved memory of scenes of objects learned through haptics. Specifically, haptic recognition of the layout of objects was overall better only when visual information about the surrounding local environment was initially available than when it was initially absent (i.e. better subsequent performance for NIV-first group). For the NIV-first group, therefore, haptic performance improved in the subsequent block of trials where visual information was not available (i.e. participant was blindfolded). In contrast, no such improvement was found for the presence of ambient visual information in a block of trials that was preceded by a block in which visual information was absent (BF-first group): the performance of participants who initially conducted the task blindfolded did not subsequently benefit from the presence of visual information. This result suggests that the initial learning conditions (i.e. seeing the surroundings or being blindfolded) affected long-term performance of the task, irrespective of the subsequent visual conditions.

Since performance in the group who initially conducted the task in the presence of vision further improved in a subsequent block, even when blindfolded, this suggests that the memory processes adopted in the first block to represent the haptic scene endured to affect subsequent performance. In contrast, performance of the group who was initially blindfolded did not show any subsequent improvement when the blindfold was removed in Block 2, suggesting that sub-optimal memory processes adopted during the initial acquisition of the task persisted throughout the experiment.

We also found that a change in the rotation of the scene produced a cost in performance across all conditions. A cost in performance with scene rotation is generally considered as evidence for an egocentric representation of visual (e.g. Diwadkar & McNamara, 1997; Simons & Wang, 1998) and haptic (Newell et al., 2005) scenes. It may indeed be the case that an egocentric representation underpins the representation of haptic scenes acquired whilst blindfolded. However, the late benefit on haptic recognition performance when participants initially viewed their surroundings suggests that an allocentric reference frame may have been adopted. Given that rotation effects were found in all conditions, the present results do not allow us to differentiate between egocentric or object-environment allocentic representations of the haptic scene. This is further investigated in the following experiments, particularly Experiment 3.

In this experiment all participants could briefly see the surrounding testing laboratory whilst they received the instructions prior to conducting the experiment. Yet it seems that pre-viewing the visual surroundings was not sufficient to affect subsequent performance in the haptic task (i.e. across all blocks). This observation suggests that it was necessary for noninformative visual cues to be present early on during the actual haptic task (i.e. in Block 1) to produce the subsequent performance benefit in the second block. Nevertheless, the concern remained that previewing the surroundings may have had some influence on task performance. We therefore decided to test a new group of participants (10 female and 4 male, aged between 19 and 31, mean age 24.64 years) whom we blindfolded before guiding them into the testing room, which was unfamiliar to all participants. As we were specifically interested in investigating why performance was reduced in the BF-first relative to the NIV-first group, these participants were presented only with the blindfolded condition followed by the NIV condition. Similar to Experiment 1, we found a main effect of scene orientation [$F(1,13) = 7.65$, $p < 0.05$] (the mean percentage errors for 0° rotation was 43.3, and for 60° rotation was 65.2) and no significant effect of visual condition [$F(1,13) < 1$] (the mean percentage errors for the BF condition was 53.6, and for the NIV condition was 54.9) on the error rate performance. We then directly compared the performance of this group with the performance of participants in the equivalent condition in Experiment 1 (i.e. the BF-first group, see Fig. 2) and found no significant difference between groups [$F(1,32) < 1$]. This finding suggests that pre-exposure to the testing room did not influence performance. Thus, it seems that in order to produce a benefit on haptic spatial performance, visual information of the surrounding environment must be available during the initial haptic scene exploration, and that previewing the surrounding environment is neither necessary nor sufficient to benefit performance.

3. Experiment 2

There were two aims to the following experiment. The first was to test whether the improvement for the NIV-first group from the first block to the subsequent blindfolded condition, was short- or long-term. If this benefit was long-term then we expected to find relatively better performance in the blindfold condition (BF) when it was preceded by the noninformative visual condition (i.e. NIV-first group) than in the BF-first group when the opposite block order was imposed, even with a delay of one week between blocks. We also included the manipulation of scene orientation since we wished to investigate whether long-term exposure to the task changed the nature of the allocentric reference frame adopted, leading from an environmental-centred (see Zuidhoek et al., 2003) to a possibly more object-centred representation.

Second, we wanted to include a control condition which would allow us to separate the effects of improved performance by repeating the task (i.e. practice effects) from the effect of our noninformative visual condition in the initial stages of the experiment. Additionally, this allowed us to investigate whether the lack of an initial benefit for noninformative vision (i.e. first block) observed in Experiment 1 could be due to insufficient time available for the effect to emerge. To that end, we doubled the number of trials in each block (i.e. NIV or BF) relative to Experiment 1 from

8 to 16 trials. In other words, the total number of trials conducted by participants in each day was 16 (i.e. in one block) which was the same as the total number of trials conducted within the one testing session in Experiment 1, (i.e. 16 trials over two blocks). Our aim here was to compare performance in the initial set of 8 trials (from 1 to 8) against performance in the later set of 8 trials (from 9 to 16) within a single block (either BF or NIV) of the present experiment in order to determine the effects of task repetition on performance. In order to be compatible with the total number of trials tested in Experiment 1, we conducted this comparison across the set of trials in the first testing block only (i.e. only the initial 16 trials were included and not trials from the testing session which occurred one week later). As stated earlier, this comparison also allowed us to investigate the emergence of the benefit of ambient visual information on haptic performance during the experimental session.

3.1. Method

3.1.1. Participants

Forty naïve undergraduate and post-graduate students from Trinity College participated in this study for pay or research credits. Twenty-two of these participants were female and 18 were male. As in the previous experiment, we pseudo-randomly assigned participants to each of the groups. There were 12 females and 8 males in the BF-first group and 10 female and 10 male participants in the NIV-first. Their ages ranged between 17 and 47 years (with the average age of the BF-first group being 20.7 years, and of the NIV-first being 24.1 years). All reported normal or corrected-to-normal vision and none reported any tactile impairments. None of the participants were involved in any of the other experiments described here.

3.1.2. Apparatus and stimuli

We used the same apparatus and stimuli as described in Experiment 1.

3.1.3. Design

Experiment 2 was based on the same three-way, mixed factorial design as Experiment 1 with block order group as the between-subjects factor (NIV-first or BF-first) and visual condition and scene orientation as the two within-subjects factors. As mentioned above, relative to Experiment 1, we included a further condition in which we doubled the number of the trials in each block (from 8 to 16), which allowed us to compare performance across two successive sets of trials within the first block in order to assess whether repeating the task inferred any specific benefits on performance within each of the visual conditions. Furthermore, we designed our task such that all scene orientations were counterbalanced across the first and second set of trials within a block. Target objects were also randomly allocated across trial sets.

3.1.4. Procedure

Experiment 2 replicated the procedure of Experiment 1 with the exception that here Block 2 was performed one week later. The experiment began with two practice trials. Each block took about 50 min to complete.

3.2. Results

Performance in all conditions was well above chance level. In order to assess whether the benefits of noninformative vision generalised over a long time delay, we first performed a three-way mixed ANOVA on the error rates with block order group (BF-first or NIV-first) as the between-subjects factor, and both visual condition across the blocks (NIV or BF) and scene orientation (0° or 60°) as within-subjects factors. We found a main effect of block order group [$F(1,38) = 15.66$, $p < 0.001$] indicating that the performance of the NIV-first group was better than that of the BF-first group. We also found a main effect of scene orientation [$F(1,38) = 92.93$, $p < 0.01$] with more errors made when the scenes were rotated (48.6% error) than non-rotated (27.8% error). There was a main effect of visual condition [$F(1,38) = 5.95$, $p < 0.05$]: as shown in Fig. 3, fewer errors were committed in the BF condition overall (37.1% error) than in the NIV condition (41.3% error). As in Experiment 1, the main effects of block order and visual condition were qualified by a significant interaction between these factors [$F(3,36) = 13.89$, $p < 0.01$]. This interaction is depicted in Fig. 3.

We used a post-hoc Tukey HSD analysis on the interaction between block order and visual condition which, as in Experiment 1, revealed that for the BF-first group haptic recognition performance did not improve from the first (BF) to the second (NIV) block [$p > 0.05$]. In contrast, performance in the NIV-first group significantly improved from the first (NIV) to the second (BF) block [$p < 0.05$]. Moreover, as found in the previous experiments, performance for the NIV-first group in the second block (BF)

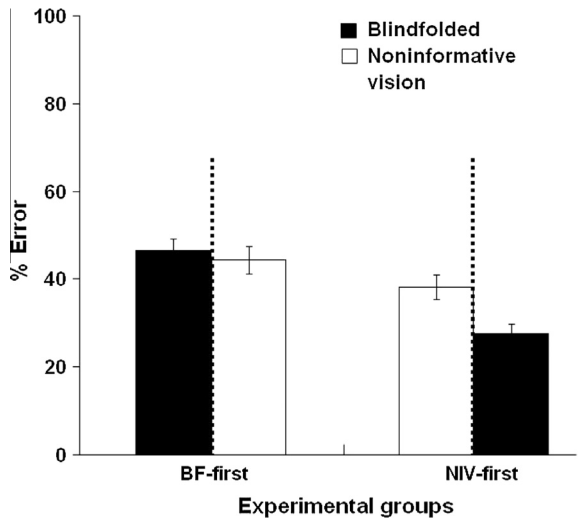

Fig. 3. Graph showing the mean percentage errors across the visual conditions in Experiment 2 with the data collapsed for the condition 'scene rotation' (see the text for details). The dotted lines indicate the one-week gap between the two visual conditions. The error bars represent ±1 standard error of the mean.

was significantly better than performance in any other condition [$p < 0.05$]. For the first block of trials, more errors were made in the BF than in the NIV condition (see Fig. 3), and this different was marginally significance [$p = 0.10$]. There were no other significant differences observed.

To meet the second aim of this experiment, we performed an intra-block analysis on the first block carried out by each group (i.e. BF-BF and NIV-NIV). Thus for each of the BF and NIV conditions we used a two-way ANOVA to compare performance across trial sequences, that is the first 8 trials with the second 8 trials (i.e. trial 9–16) in the first Block, and scene rotation. For the participants in the BF-first group, there was a slight improvement in performance from the first to the second set of 8 trials in the block (from 47.1% to 46% errors) although this difference was not significant [$F < 1$]. As in the main analysis, there were fewer errors made when scenes were not rotated relative to rotated scenes [$F(1,18) = 51.35$, $p < 0.01$]. The interaction between trial sequence and scene rotation was not significant [$F < 1$]. For the participants in the NIV-first block, a greater improvement on performance was found from the first to the second set of 8 trials in the block (the mean percentage errors reduced from 41.9% to 32.6% respectively). This difference was marginally significant [$F(1,18) = 3.94$, $p = 0.06$]. Again, performance to scenes which were not rotated was better than that to rotated scenes [$F(1,18) = 26.17$, $p < 0.01$] but scene rotation did not interact with trial sequence [$F < 1$].

3.3. Discussion

As in Experiment 1, performance in the second testing block did not improve for participants who were blindfolded in the first block (BF-first group), even though there was a 7-day interval between blocks. Our results for the noninformative vision group replicated those found in Experiment 1. Furthermore, these findings suggest that any benefit of seeing the surrounding room during task acquisition seems long lasting, at least up to one week, suggesting that the initial presence of visual information promoted more optimal processes for representing haptic scene information in long-term spatial memory. Moreover, the lack of improvement of the participants who were initially blindfolded also suggests that the absence of vision during initial task acquisition has long term effects on performance. As previously mentioned, it is likely that context-dependent memory might support these long-term effects. For example, Smith and Vela (2001) reported that context-dependent learning effects were found also for intervals of one week (see also Tulving & Thomson, 1973). In any case, it is interesting to note that both optimal and non-optimal memory processes adopted during initial task acquisition continue to persist over the long-term, at least for the duration of one week.

Our intra-block analysis revealed an interesting finding that learning rates differed across participant groups assigned to the different visual conditions. Specifically, performance improved from the first half to the second half of trials in the first block for participants who were able to view their surroundings during the task. To add further support to our claim that initially viewing one's surroundings benefits haptic performance, we compared the relative benefit on performance between the 8 trials in the NIV and BF blocks for the NIV-first group in Experiment 1 (i.e. a reduction of 10.94% in error), with the benefit in performance between the first 8 and second 8 trials in the NIV block for the NIV-first group in Experiment 2 (a reduction of 9.27% error). This difference was not significant [$t(1,38)= 0.29$, $p = 0.77$] suggesting that the benefit for noninformative vision is genuinely produced by having initially undergone the NIV condition. Moreover, this result suggests that, although it takes time to develop, there is a direct benefit for noninformative vision (i.e. within the first block) on haptic scene recognition performance. In contrast, however, no such improvement was found for participants who were blindfolded during the first block. This finding adds further support to our argument that the absence of visual information, albeit unrelated to the specific goals of the task, promotes the adoption of non-optimal spatial memory strategies. Furthermore, these strategies appear to be long-lasting and are unaffected by the subsequent availability of visual information in a later test.

The above results also replicate the findings of Experiment 1 with a minor exception: here we found that the difference in performance across the NIV and BF conditions reached significance (with better overall performance in the blindfolded condition than in the noninformative vision condition, as shown in Fig. 3). Although there was a similar trend in performance across these conditions in Experiment 1, the difference failed to reach statistical significance. As in Experiment 1, this main effect is qualified by an interaction between block order and visual condition, therefore, this result is likely due to the improvement in performance of the NIV-first group in the second (BF) block, i.e. when these participants were blindfolded one week later. Although the reason why the overall difference across BF and NIV becomes significant in Experiment 2 is unclear, it might be due to the overall increase in the number of trials tested in Experiment 2 which may have allowed performance to further improve over time (as observed across the first and second set of trials in the first block for the NIV group only). This is supported by the greater variability in responses observed in Experiment 1 (standard deviations were 22.87 for BF-first and 18.98 for the NIV-first group) than in Experiment 2 (standard deviations were 15.29 for BF-first and 12.15 for the NIV-first group). In general, however, although performance was marginally better overall in Experiment 2 relative to Experiment 1,[4] the pattern of results remained the same: whether visual information is available during intial task acquisition or not has an effect on performance in the subsequent block of trials.

In line with previous perceptual studies, the benefit of ambient vision on haptic scene recognition in Experiment 1 and 2 might suggest a shift in the nature of the representation from an egocentric to a more allocentric code when noninformative vision is available (see e.g. Millar & Al-Attar, 2004, 2005; Zuidhoek et al., 2004). However, the

[4] A comparison between the results obtained across Experiment 1 and 2 showed a significant difference [$F(1,78) = 4.03$, $p = 0.048$].

finding that a change in scene orientation reduced performance, even when visual information was initially available, is compatible with the adoption of either an allocentric (e.g. Kappers, 2007; Newport et al., 2002; Volcic & Kappers, 2008) or egocentric reference frame. Moreover, the effect of scene rotation suggests that if an allocentric reference frame was adopted, it is more likely to be environment-centred than object-centred, since scene rotation may disrupt the relative directions among the objects and the environment that was originally used to represent the scene (Mou et al., 2007). We investigated whether an allocentric or egocentric reference frame is triggered by noninformative vision in the following Experiment. Specifically, we introduced a change of environment from one block of trials to the next. A change in environment would not be expected to affect an egocentric or object-to-object allocentric representation of the haptic scene. However, it would affect an environment-centred representation. Therefore, we might expect that a change of environment would disrupt performance if the haptic representation was based on an environment-centred reference frame but not if an egocentric reference frame was adopted.

4. Experiment 3

In the following experiment we investigated the adaptability of the effect of non-information by changing the environment across blocks. Specifically, we tested whether we could replicate the improvement from the first (NIV) to the second (BF) block when participants were moved to a different environment between the two blocks. If the benefit on performance in the blindfold condition following the NIV block was reduced by the change of environment (i.e. relative to performance in the previous experiments when no environmental change occurred) then this result would suggest that the benefit of non-informative vision on the haptic recognition of a scene of objects was mediated by a reference frame which was based on features from the environment.

The benefit on performance in the blindfolded block for the NIV-first group suggests that these participants could still avail of the information from their surroundings in the second block of trials. This may have occurred for several reasons. First, participants may have been able to evoke a mental image of their visuo-spatial surroundings when blindfolded and memory of this environment endured for at least one week. In other words, it is possible they could continue to avail of an allocentric environment-centred reference frame through mental imagery. If so, then it is possible that this mental image may be evoked in any context, allowing for the benefits of initially seeing the surroundings to generalise to other environments or contexts. On the other hand, there may be important reasons why mental images of visual surroundings may not be adaptable and are consequently context-specific. For example, it would be important not to rely on visual images from memory when placed blindfolded in a new environment as any consequent actions (e.g. navigation, object search, etc.) would be inappropriate. In this case, it would be more appropriate to rely on spatial cues from other sensory modalities, such as audition or olfaction, as is the case in persons who are blind (Röder et al., 1999). As such, a change in environment would be expected to reduce, if not eliminate, any benefits on haptic performance from previously viewing a different environment.

4.1. Method

4.1.1. Participants

Twelve naïve undergraduate and postgraduate students from Trinity College, School of Psychology participated in this study for pay or research credits. Four of these participants were female and eight were male. Their ages ranged between 18 and 58 (with a mean age of 28.3 years). All reported normal or corrected-to-normal vision and none reported any tactile impairment. None participated in any of the other experiments reported here.

4.1.2. Apparatus and stimuli

The apparatus and stimuli were the same as described in Experiment 1. Two different laboratory rooms in the School of Psychology, Trinity College were used in this experiment. The rooms were located along the same corridor, they differed slightly in overall shape, size and furniture contents, but neither contained windows and the access door faced the same geographical position. We also positioned the apparatus according to different 'world-centred' co-ordinates in each room, such that participants were seated with their backs against the door in one room and faced global North, but were seated perpendicular to the door in the second room and faced global East. Both laboratories were unfamiliar to the participants prior to testing.

4.1.3. Design

The experiment was based on a one-way, within-subjects design with visual condition (NIV or BF) as the factor. There were eight trials in each condition. We did not test for effects of scene orientation here since this effect was already established in the previous experiments and, more importantly, because scene rotation did not interact with any of the other experimental conditions. Here we were specifically interested in whether a change in environment disrupted the benefit of non-informative vision on a subsequent haptic recognition task whilst blindfolded.

4.1.4. Procedure

Participants were guided whilst blindfolded into the first laboratory. All participants were first required to conduct a single block of trials in the NIV condition, i.e. they could see their surroundings. On completion of this first block of trials, the participants were then taken to another testing room and were again blindfolded before entering. When they were guided into the (unfamiliar) testing lab they were explicitly informed that the new environment was different in size, shape and contents from the previous room. The experiment took about 50 min to complete.

4.2. Results

The mean percentage errors (and standard deviation) for each of the conditions was 28.1% (6.56) for the initial NIV block and 27.6% (5.93) for the second BF block. Performance in both of these conditions was above chance level. We conducted a t-test on the visual condition and failed to find evidence of a significant change in performance across the blocks [$t(1,11) = 0.07$, $p > 0.05$].

4.3. Discussion

The result of the present study, in which we failed to find improved performance in the BF block relative to the initial NIV block, suggests that the improvement in performance from the initial noninformative vision block to the blindfolded block of trials in the previous experiments was context- or environment-dependent. In the present experiment, although the task remained unchanged, the benefit on performance from an initial block of NIV trials to the subsequent blindfolded block did not occur when there was a change in the environmental context: when participants performed the second block of trials blindfolded, and in a new environment, their performance did not improve contrary to the results of Experiment 1 and 2. To establish whether performance differed across experiments, we compared performance in the present experiment with performance in the equivalent conditions (NIV followed by BF blocks, excluding performance to trials with scene rotation) in Experiment 2 (i.e. with mean error rates of 27.5% for NIV and 20% for BF trials). To that end, we conducted a 2 (Experiment) by 2 (visual condition) between-subjects ANOVA on the error rates. Overall the difference across the two experiments was not significant [$F < 1$], but there was a main effect of visual condition [$F(1,30) = 4.5$, $p < 0.05$]. This main effect was due to overall better performance in the second block (BF) than the first (NIV) block of trials. This is likely due to the relatively large improvement in the second block in Experiment 2 as suggested by the interaction between experiment and visual condition which was marginally significant [$F(3,28) = 3.44$, $p = 0.07$]. As a comparison between the performance in the second (BF) block across experiments was our main goal, we conducted a post-hoc analysis (Tukey HSD) on the interaction. This revealed no difference in performance across experiments in the first (NIV) block, but relatively worse performance in the second (BF) block of Experiment 3 (following a change to a different room) compared to Experiment 2 (without a change in room). This finding adds support to the argument presented earlier that the benefit on haptic memory for scenes when visual information is available is context dependent.

The results suggest that, although visual mental imagery of the previous environment may have been evoked when the environment changed, this was not sufficient to improve performance in a subsequent block. This finding is consistent with previous literature on context-dependent effects on learning and memory, in that memory performance was dependent on specific knowledge of the local environment or context (see e.g. Godden & Baddeley, 1975; Smith & Vela, 2001). Moreover, the result of this experiment strongly suggests that the reference frame most likely adopted when noninformative vision is initially available is an allocentric environment-centred reference frame, since a change in environment disrupts the benefit of noninformative vision on a subsequent block of trials. In contrast, a change of environment would be unlikely to affect the adoption of either an egocentric or object-to-object reference frame.

An alternative account of these findings could be that the participants' motion from the first to the second testing room and/or the change in global position from one lab to the next disrupted performance between the blocks. We consider this an unlikely possibility given that in Experiment 2 performance significantly improved across the two blocks for the NIV-first group, despite a (presumably) substantial amount of self-motion occurring during the one-week delay between testing blocks. Furthermore, our previous research suggests that memory representations for haptic scenes are efficiently updated with observer motion (Pasqualotto et al., 2005).

We did not rotate the scenes during the test session in this experiment as the effect of rotation was already established in the previous experiments and it did not appear to affect performance across the experimental conditions. However, trials in which the scene could be rotated may have contributed to the overall difficulty of the previous tasks and by not including trials in which the scene was rotated in the current experiment we may have rendered the task too easy to observe improved performance across blocks. With this in mind, we compared performance for equivalent conditions between the current experiment and Experiment 2. That is, we compared performance in the first block of trials in the present Experiment (i.e. before the participant changed room locations) to performance in the first block in Experiment 2, for the NIV-first group only, and for trials in which the scene was not rotated.[5] Error rate performance across the present experiment (28.1%) and Experiment 2 (27.5%) was not significant [$F(1,18) < 1$], suggesting that the lack of difference across the NIV and BF conditions in the present Experiment was not due to changes in the difficulty of the task.

Having found support for noninformative vision triggering an allocentric environmental-centred reference frame, the next step was to elucidate which specific visual attributes of the ambient environment are used to establish such a reference frame. To that end, in the following experiment we manipulated the type of ambient visual features viewed by the participants during haptic scene recognition.

5. Experiment 4

Although the results of our previous experiments suggested that noninformative vision improves memory for the spatial location of objects learned through touch, it is not clear what aspect of the visual information results in

[5] Since Experiment 2 had twice the number of trials as Experiment 3, by excluding data from the rotated trials in Experiment 2, this renders an equivalent number of trials to compare across experiments. The same number of trials were not tested in Experiment 1 therefore we did not include a comparison between the same conditions with the present experiment.

this benefit. For example, the visual surroundings included both spatial (i.e. geometric) and object information (i.e. landmarks), as well as other non-spatial information such as hue or luminance. Thus, vision may provide the spatial context within which haptic space is represented or vision may provide landmark positions to which the positions of the haptic objects are encoded (see e.g. Postma et al., 2008b). The aim of this experiment was to address this issue by manipulating the nature of the visual information to which the participants were exposed. To this end we created virtual displays of rooms containing three different types of visual information; visuospatial information only (i.e. a structured room), visual landmarks only (i.e. items of furniture alone) or spatial information with landmarks (i.e. a furnished room) (see Epstein & Kanwisher, 1998, for a similar design). We also included a baseline condition in which non-spatial visual stimulation was provided by a uniform grey image. A non-spatial visual stimulus consisting of a uniform grey background is akin to visual perception of lightness in the absence of spatial information and has previously been shown by Millar and Al-Attar (2005) not to influence haptic memory performance.

We compared haptic scene recognition performance to each of the visual displays of room scenes against performance on the haptic task when a uniform grey visual background was presented. Although the issue of which reference frames are used in visuo-spatial tasks is debated, several studies on children (Gouteux & Spelke, 2001) and animals (Chiandetti & Vallortigara, 2007; Sovrano, Bisazza, & Vallortigara, 2003; Wang & Spelke, 2002) have provided convincing evidence that spatial behaviour is based on environmental geometry (e.g. room shape) and not on object landmarks. On the other hand, recent research on adult humans have shown that both geometric and object landmark information are integrated into visuospatial memory for the purpose of spatial navigation (e.g. Foo, Warren, Duchon, & Tarr, 2005; Newman et al., 2007). Moreover, Kelly and Avraamides (2011) provided evidence for the use of geometric visual information on the subsequent acquisition of a haptic scene, although their study did not contrast this effect with object landmarks. Spatial mechanisms may differ according to the working space (Piccardi et al., 2010), therefore it is unclear what type of visual information is necessary for efficient haptic spatial perception based on small scales. We predicted that haptic spatial memory would benefit from noninformative vision provided visual information was available in the scene and not just lightness perception. However, we were uncertain as to whether it was necessary to have geometric or object landmark or both types of visual information available in order to observe a benefit on haptic performance.

5.1. Method

5.1.1. Participants

Thirty-six naïve undergraduate and post-graduate students from the Trinity College participated in this study for pay or research credits. Of these participants 21 were female and 15 were male. Their ages ranged between 18 and 62 years.[6] Participants were pseudo-randomly assigned to each of the visual information conditions: 'spatial information only' (4 males and 8 females, mean age of 26.5 years); 'spatial information plus landmarks' (6 males and 6 females, mean age of 31.3 years); 'landmarks only' (5 males and 7 females, mean age of 24.2 years). All reported normal or corrected-to-normal vision and none reported any tactile impairment. None participated in any of the other experiments reported here.

5.1.2. Apparatus and stimuli

The same haptic object scene used in the previous experiments was again used here for testing. In this experiment participants positioned their heads on an adjustable chin rest positioned in front of the object scene and wore a head-mounted display (HMD; Graphics Stereo 3D™) that was, in turn, mounted on a fixed support. This HMD was connected to a computer (Dell Optiplex GX270™) which presented the virtual scene images. In order to avoid any effect of noninformative vision produced by the real environment, the details of the surrounding room were occluded from vision by seating the participant into a cabin. The cabin, consisting of internally black painted wooden walls, measured 75 cm by 160 cm by 60 cm in width, height and depth respectively. Participants were also blindfolded before entering the testing room and the blindfold was removed only when they were seated inside the cabin. To further ensure participants could not view their surroundings, the testing room (which was windowless) was fully darkened before the participant was guided inside and throughout the test. The occluding screen was used as in the previous experiments to maximise similarity across the experiments: as in these previous experiments, participants could not view their arms or hands when conducting the task.

The visual stimuli consisted of three coloured images of scenes from virtual environments (of which each participant saw only one during the experiment) and one non-spatial, uniform grey scene. These images were created using 3D Studio Max™ graphic software. Each image was projected onto the HMD and, once the HMD was worn by the participant each image subtended a visual angle of approximately 142° in the horizontal plane. The images were either a virtual empty room (geometric or spatial information only); a virtual room with four pieces of furniture (spatial information with landmarks); landmarks only or a uniform grey image (no spatial nor landmark information). Fig. 4 provides an illustration of the visual stimuli used in the experiment.

5.1.3. Design

The experiment was based on a one-way, between-subjects design with visual information as the main factor (spatial only, landmarks only or spatial plus landmarks). All participants first performed a baseline condition which consisted of a block of trials where a non-spatial visual stimulus comprising a uniform grey image was presented during haptic testing. Following the baseline block, participants were randomly assigned to one of the three virtual

[6] Although cognitive studies on ageing often use the age of 60 to represent the beginnings of the 'older age' category, in our study we observed no differences in performance as a consequence of age.

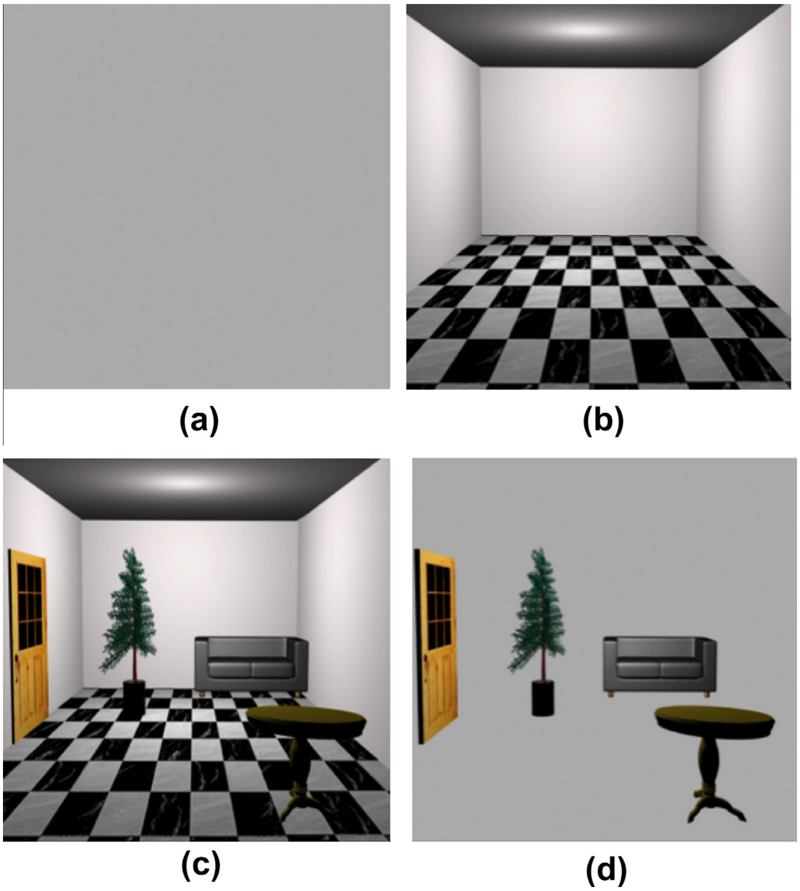

Fig. 4. An illustration of the visual conditions used in Experiment 4: (a) baseline condition, no spatial information provided; (b) spatial information only; (c) spatial information and landmarks; (d) landmark objects only.

display conditions presented during the task. In other words, each participant viewed the uniform grey image (Fig. 4a) and only one of the three images depicting spatial information (Fig. 4b, c, or d). For each participant there were a total of 16 trials (eight trials in each of the baseline and visual blocks). As in Experiment 3 we did not rotate the scene during the task. We felt that it was unnecessary to test participants on this condition in this experiment for two reasons: first we had already established a robust effect of scene orientation in Experiments 1 and 2, and, more importantly scene rotation did not interact with any other variable in those experiments.

5.1.4. Procedure

Participants were blindfolded outside of the testing lab and guided into the room. Once seated at the apparatus, they were instructed to remove the blindfold and to place their head on the chin rest. The chin rest was subsequently adjusted until the participants were seated comfortably whilst viewing the images on the supporting HMD.

The participant received the same instructions with regard to the haptic task as in the previous experiments. They were told that they would be presented with different visual stimulation during the experiment but that this information would not help them to perform the haptic task. The experiment began with three practice trials on the haptic task and the experimenter provided feedback on the performance after the practice trials only. The task was the same as described in previous experiments.

Each participant was tested in two separate blocks: baseline (as shown in Fig. 4a) followed by the experimental condition to which they were randomly assigned (as shown in Fig. 4b, c, or d) and could take a self-timed break between blocks (but they could not see the surrounding room). The experiment took around 40 min for each participant to complete.

5.2. Results

The mean percentage error across each of the conditions was 18.8%, 22.9%, 31.8% for the 'spatial information only' 'spatial information plus landmarks' and 'landmarks only' conditions respectively. The mean error performance to the non-visuospatial baseline condition in each of these visual conditions was 36.5%, 34.9% and 33.3% respectively. The benefit on haptic performance of each of the visual scene conditions relative to the baseline condition of a uniform visual display was calculated as follows: for each participant we subtracted the error performance in each of the main experimental condition (i.e. the three visuospatial conditions) from the error performance in the non-spatial visual baseline condition. This relative benefit on performance across each of the visual conditions is plotted in Fig. 5.

We first determined whether the relative benefit in performance in each condition was greater than baseline, i.e. greater than 0%. Using single-sample t-tests we found that performance to the 'spatial information only' and the 'room with objects' was greater than 0 [$t(1,11) = 4.14$, $p < 0.01$ and $t(1,11) = 4.10$, $p < 0.01$ respectively], but that performance to the object 'landmarks only' condition (i.e. without the room context) was not greater than baseline [$t(1,11) < 1$]. We then conducted a one-way, between-subjects ANOVA on the benefit on haptic performance across the three visual conditions and found a significant effect [$F(2,33) = 6.25$, $p < 0.01$]: a post-hoc Tukey HSD analysis revealed that when participants viewed either the room only (i.e. spatial or geometric information) or the room with objects, the benefit on haptic memory performance was significantly greater than when they viewed the landmark objects alone [$p < 0.5$]. Moreover, there was no difference in performance between the room only and room with objects conditions. For completeness, we compared performance in the non-spatial visual (baseline) condition only across the three experimental groups and found no significant differences [$F(2,33) < 1$], suggesting that there were no pre-existing differences across the groups in baseline performance that might explain the relative benefit across the other visual conditions. Our finding suggests that haptic scene recognition performance is affected by visual information which includes visuospatial or geometric information.

5.3. Discussion

Our results suggest that visuospatial (often called geometric) information provided during haptic scene exploration specifically enhanced the memory of haptic scenes, even though this visual information was not directly relevant to the task. This enhanced performance mediated by viewing either the virtual empty room or the furnished room, was not simply due to a practice effect since performance did not equally improve across all visual conditions. Moreover, the presence of the visual landmarks in the virtual room (i.e. the furnished room) did not improve performance relative to the empty room suggesting that objects were neither necessary nor sufficient in the image for improved performance. Our findings suggest that noninformative vision enhances haptic memory provided that visuospatial information is available in the visual image.

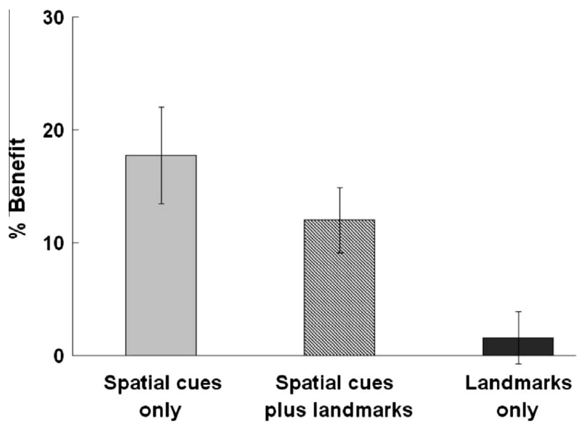

Fig. 5. Graph showing the mean percentage benefit for the virtual visual environments presented in Experiment 4. The plotted data represent the difference between the mean percentage errors in the baseline condition (i.e. grey image) minus the mean percentage errors in each of the visual condition. The error bars represent ±1 standard error of the mean.

These results complement other findings that spatial geometry is more salient than landmark information for visuospatial tasks such as navigation (e.g. Lee, Sovrano, & Spelke, 2012; Wang & Spelke, 2002). Moreover, when both spatial information and landmarks were available it is possible that they were integrated in the visual scene thus providing a richer visual reference frame (see Newman et al., 2007) to which the haptic information was referred and performance in the haptic task consequently improved. However, there was no benefit on performance when object landmark information alone was available relative to visuospatial information alone, suggesting that landmark information may not have been used. Furthermore, when landmark objects were added to the room in the visual image there was no additional benefit observed on haptic memory performance. Although in some cases isolated visual landmarks can be efficiently used in spatial tasks performed in natural settings (such as for navigation purposes, see Steck & Mallot, 2000), our results suggest that landmarks alone were not sufficient to provide a reference frame to which haptic objects were represented, at least not one which was any more effective than a non-spatial visual image (i.e. baseline condition). In sum, these, results suggest that the benefits of noninformative vision are confined to specific types of visual cues: neither diffuse visual information nor the presence of visual object landmarks alone facilitate a benefit on haptic performance. Instead visual images which contained visuo-spatial information were necessary to affect scene recognition performance through touch.

Note that, on face value, the baseline condition in the present experiment might be compared to the initial blindfold condition in the previous experiments, leading to the conundrum that the results appear to differ across these experiments (i.e. there is a benefit on haptic perception in subsequent blocks in the present experiment only). We believe that such a comparison between the visual conditions is unwarranted: on the basis of previous research, we consider the blindfold condition as akin to visual deprivation, whereas the baseline condition in the present study involves direct visual stimulation (albeit with a homogenous pattern). Neuroimaging studies support this view in that differential brain activation is found between conditions involving short-term visual deprivation (i.e. eyes closed, eyes open to darkness) and visual stimulation with a homogenous background (e.g. eyes open to dim light, or fixation cross) (see e.g. Marx et al., 2004; Nir, Hasson, Levy, Yeshurun, & Malach, 2006; Zou et al., 2009). Moreover, Marx et al. (2004) reported differential effects of these visual conditions on activations in other sensory regions of the brain. The results of the present study clearly show, however, that it is the specific spatial nature of the visual stimulation which has a benefit on haptic perception.

These behavioural findings reflect recent evidence from the neuroimaging literature on the neural underpinnings of visual scene perception. For example, several studies have now provided evidence for the role of the parahippocampal cortex or parahippocampal place area (PPA) in visual scene perception (Epstein & Kanwisher, 1998; Walther, Caddigan, Fei-Fei, & Beck, 2009) or even single objects which evoke a spatial presence (Mullally & Maquire, 2011) and that activation patterns in the PPA are associated with changes in scene viewpoint (Epstein, Graham, & Downing, 2003). More pertinently, Epstein and Kanwisher (1998) used visual stimuli similar to those used in the present study (furnished room, empty room and furniture shown against a blank background) and found that the activation levels in the parahippocampal place area (or PPA), were equivalent across visual images of furnished or empty rooms and, in turn, greater than for images of furniture alone. Moreover, the results of a study reported by Kravitz, Peng, and Baker (2011) suggests that the nature of the representations within the PPA may be more related to the spatial content of the scene (i.e. whether the scene is ‘open’ or ‘closed’) than its semantic context.

6. General discussion

In this series of experiments we found that ambient or ‘noninfomative’ visual information could subsequently enhance haptic memory of scenes of objects if it were available during initial task acquisition (Experiment 1) and that this benefit endured over a relatively long interval of one week (Experiment 2). We confirmed that the relative cost to haptic spatial memory when visual information was absent (i.e. obscured by a blindfold) during initial task acquisition persisted whether the blindfold was removed after a delay of either several minutes (Experiment 1) or one week (Experiment 2) between testing blocks. Furthermore, haptic scene performance improved whilst the participant was continuously able to view their surroundings but no such improvement was observed over the same number of trials if the participant was blindfolded (Experiment 2). In Experiment 3 we established that a change in visual context seemed to disrupt the long-term benefit of noninformative visual information, suggesting that the visual context provided during the initial stages of task acquisition is important for haptic spatial memory of an array of objects. Additionally, the result of Experiment 3 suggested that noninformative vision triggered the use of an allocentric environmental-centred reference frame. Finally, we determined that specific visuo-spatial information available in the ambient environment, and not general visual information involving e.g. object landmarks or non-spatial information, promotes a benefit on haptic memory performance (Experiment 4).

Our results support the previous literature on the role of noninformative vision on tactile discrimination and haptic perception (e.g. Kennett et al., 2001; Newport et al., 2002) and are consistent with recent studies reporting equivalence between spatial learning based on vision or haptics (Giudice et al., 2009, 2011). Nevertheless, the results of the present experiments extend these findings in two important ways. First, our results show that over time, the presence of visuo-spatial information improves memory for, and subsequent recognition of, complex haptic scenes. Thus our findings extend previous findings on haptic perceptual performance into the domain of spatial cognition,

Second, haptic memory for the spatial layout of a scene was better when the surrounding room could be viewed in the initial block of trials than when it could not. This finding suggests that by providing visual information of the surrounding environment during haptic scene exploration a more allocentric representation of the scene was promoted, as has been suggested by previous researchers (Kappers, 2007; Millar & Al-Attar, 2005; Newport et al., 2002; Postma et al., 2008b; Volcic & Kappers, 2008). In particular, our findings suggest that the nature of this allocentric frame is more likely to be an environment-centred rather than an object-centred reference frame. We can state this for several reasons. First, an object-centred reference frame would more likely predict orientation-independent haptic memory of scenes (Easton & Sholl, 1995; Sholl & Nolin, 1997), unless a scene reference axis could be recovered through the specific alignment of objects (Mou et al., 2004, 2009). A salient scene axis was unlikely to emerge across trials in our experiment due to the random positioning and orientation of the objects. In contrast, performance was orientation-dependent when tested (Experiments 1 and 2). Indeed, a cost on performance with scene rotation persisted whether or not visual information was available. Second, the results of Experiment 3 suggest that the benefit on haptic scene recognition is disrupted when there is a change in the environment-centred information. Finally, the results of Experiment 4 provide further support to the idea that specific cues from an allocentric, environment-centred visual reference frame facilitated haptic memory.

Our results also suggest that the benefit of visual information on the representation of haptic scenes can depend on the initial learning context (see e.g. Godden & Baddeley, 1975), during which optimal processes for representing haptic spatial information were adopted. In particular, when the haptic spatial task was initially conducted in the presence of visual information, the relative benefit on performance generalised to a subsequent block of trials in which the visual information was obscured with a blindfold. Moreover, the benefits of noninformative visual cues present during the initial acquisition of the haptic task were not affected by a change in the visual conditions (c.f. Kelly & McNamara, 2010) but were long-term and lasted for one week at least. In contrast, participants who were blindfolded in the initial block of the task, continued to perform relatively poorly even when the blindfold was removed in the subsequent block, suggesting that sub-optimal processes for representing haptic spatial information were initially adopted. Moreover, the early adoption of specific memory processes seemed to endure whether ambient visual information was removed or revealed, suggesting that these processes are robust over time. In contrast, a change in environment appears to disrupt performance suggesting that the effects are not robust to changes in spatial context.

Although it is not entirely clear what allows for the continued benefit of noninformative vision on haptic spatial performance, the results of some previous studies provide some insight. For example, it could be possible that participants who could initially view their surroundings used mental imagery of the room in subsequent blocks to help localise the haptic objects based on an imagined allocentric frame (see e.g. Aguirre, Detre, Alsop & D'Esposito, 1996; Boyce & Pollatsek, 1992; Epstein & Kanwisher, 1998, on the effect, duration and neural substrates of spatial memory). However, this does not explain why participants who had the blindfold removed did not subsequently improve on the haptic task in the presence of visual cues. Instead, our findings, specifically those of Experiment 3 which found that the benefit on haptic performance of noninformative vision did not generalise to a novel visual environment, suggest that context-specific strategies acquired during the initial stages of the task (i.e. Block 1) affected performance in subsequent trials of the task.

An alternative explanation of the long-term effect of visual information on haptic spatial memory may be provided by the findings of Waller & Hodgson, 2006; (see also Hodgson & Waller, 2006). These authors proposed two types of parallel visuo-spatial memory storage, one more precise, but involving a more 'volatile' or transient spatial memory and one more coarse but involving a 'lasting' or enduring spatial memory (see also Creem & Proffitt, 1998; Huttenlocher, Hedges, & Duncan, 1991). In their experiments Waller and Hodgson used disorientation (i.e. self-spinning on a stool) and self-rotation to disentangle the role of each memory system within the visual domain. They argued that disorientation and self-rotation triggered a 'switch' towards the use of a more enduring but course spatial representation. If blindfolding acts in a similar way as spatial disorientation on the consequent representation, then it is possible that the absence of visual detail triggered a coarser spatial representation of the haptic scene in our tasks. Moreover, the finding that performance did not improve in the second block of trials, i.e. subsequent to the block in which the participant was blindfolded, suggests that the initial representation is enduring. However, although detailed representations are more likely to occur in the presence of visual information, the finding that the benefit of viewing the surrounding environment on haptic spatial performance generalises to a subsequent block of trials in which the participant is blindfolded (even with an intervening gap of one week) questions the idea proposed by Waller and Hodgson that such representations are 'transient'.

The findings of the current experiments help elucidate the interactions between the spatial modalities for the purpose of efficient spatial cognition. Although our knowledge of the neural processes underpinning these cross-modal interactions is relatively poor, recent research has provided some insights. For example, our results are in line with recent findings suggesting a functional equivalence between vision and touch for the purpose of spatial cognition (see e.g. Loomis et al., 2007; Newell, 2004; Pascual-Leone & Hamilton, 2001). Indeed, Wolbers, Wutte, Klatzky, Loomis, and Giudice (2011) reported that the parahippocampal place area (PPA) was activated by both visual and tactile inputs. Other findings related to the role of vision on tactile perception suggest it is possible that direct modulation of activation in somatosensory regions of the brain by visual input may mediate these effects (see e.g., Forster & Eimer, 2005). Clearly, however, it is not yet known whether, or how, such direct cross-sensory interactions occur for more cognitive tasks such as spatial memory.

Nevertheless, our behavioural results have important implications for our understanding of how visual information modulates haptic processing and help elucidate the multisensory processes involved in the representation of spatial information in memory. Furthermore, these finding may have a direct application on the design of devices which enhance human performance by providing information across more than one sensory modality (see e.g. Proulx, Brown, Pasqualotto, & Meijer, in press).

7. Conclusion

In sum, we found that viewing one's surroundings during initial task acquisition confers a benefit on haptic spatial cognition. This benefit emerges late in task acquisition, but persists despite the subsequent absence of ambient visual information. We argue that ambient or 'noninformative' visual information provides an allocentric reference frame which facilitates the storage of a robust representation of haptic object locations in memory. Moreover, we provide evidence that this reference frame is likely to be based more on an environment-centred rather than object-centred allocentric representation. A change in the ambient environment during the task disrupts this process, suggesting an important interplay between context-dependent processes and the adoption of optimal memory representations.

Acknowledgements

This research was funded by a Higher Education Authority, Programme for Research in Third Level Institutions (PRTLI) Grant, Cycle 3, awarded to Trinity College Institute of Neuroscience, of which FNN is a member, and the EU IST Programme, 'Sensemaker' Project (IST-2001-34712).

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