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Brief article

Cross-sensory transfer of reference frames in spatial memory

Jonathan W. Kelly [a,*], Marios N. Avraamides [b]

[a] Department of Psychology, W112 Lagomarcino Hall, Iowa State University, Ames, IA 50011-3180, United States
[b] Department of Psychology, University of Cyprus, P. O. Box 20537, 1678 Nicosia, Cyprus

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ABSTRACT

Two experiments investigated whether visual cues influence spatial reference frame selection for locations learned through touch. Participants experienced visual cues emphasizing specific environmental axes and later learned objects through touch. Visual cues were manipulated and haptic learning conditions were held constant. Imagined perspective taking when recalling touched objects was best from perspectives aligned with visually-defined axes, providing evidence for cross-sensory reference frame transfer. These findings advance spatial memory theory by demonstrating that multimodal spatial information can be integrated within a common spatial representation.

1. Introduction

Accurate spatial memory retrieval is fundamental to behaviors ranging from locating one's keys to finding a new route home. Because locations are necessarily relative, they must be represented within a spatial reference system. One of the most ubiquitous findings in spatial memory research is that retrieval is best along one or two directions, considered evidence for a reference frame along the facilitated directions (Klatzky, 1998). Behavioral and neuroscientific research points to an important distinction between egocentric and environmental frames (Pani & Dupree, 1994; Nadel & Hardt, 2004). Research on visually-acquired spatial memories (Kelly & McNamara, 2008; McNamara, Rump, & Werner, 2003; Shelton & McNamara, 2001a) highlights the interaction between egocentric and environmental reference systems, whereby reference frames are selected from experienced views aligned with salient environmental axes.

Non-visual senses also provide access to egocentric and environmental information (Millar & Al-Attar, 2004). Accordingly, reference frames characterize memories of locations learned through touch (Newell, Woods, Mernagh, & Bulthoff, 2005; Pasqualotto, Finucane, & Newell, 2005), audition (Yamamoto & Shelton, 2009), proprioception (Valiquette, McNamara, & Smith, 2003; Yamamoto & Shelton, 2005), and spatial language (Avraamides, 2003; Avraamides & Kelly, 2010; Mou, Zhang, & McNamara, 2004; Wilson, Tlauka, & Wildbur, 1999). However, it is unknown whether locations learned through different senses are stored within separate representations organized by separate reference frames or if they can be integrated into a common representation organized by a common reference frame. For example, locations learned through vision and touch could be represented in separate egocentric or environmental reference frames, or within common egocentric or environmental reference frames. The current project addresses this issue by investigating cross-sensory reference frame transfer during multimodal spatial learning.

Research on multimodal spatial learning provides mixed evidence for the common reference frame hypothesis. Yamamoto and Shelton (2005) had participants learn locations through vision and proprioception, and later perform judgments of relative direction (JRD), which entail pointing to remembered objects from imagined perspectives. JRD performance revealed two preferred orientations, suggesting that participants stored separate modality-specific representations using separate reference

* Corresponding author. Tel.: +1 515 294 2322.
E-mail address: jonkelly@iastate.edu (J.W. Kelly).

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frames. In another study (Giudice, Klatzky, & Loomis, 2009), participants learned some objects through vision and others through touch. JRD tested intramodal or intermodal object pairs. Temporal separation of learning modality led to better performance on intramodal than intermodal trials, suggesting that objects from different modalities were characterized by separate reference frames. Temporal overlap of learning modality led to similar performance on intermodal and intramodal trials, indicating that locations were integrated into a common reference frame. However, it is also possible that locations were represented in separate, globally aligned reference frames, eliminating transformation costs. The authors reject this separate-but-equal hypothesis in favor of the common reference frame hypothesis because it offers no principled explanation for the observed functional equivalence.

In sum, existing research on reference frames after multimodal learning does not clearly answer whether locations learned through different modalities are stored within separate representations organized by separate reference frames or if they are integrated into a common representation organized by a common reference frame. The current experiments took a unique approach to this question by examining cross-sensory reference frame transfer, using a paradigm previously developed to study reference frames during spatial memory microgenesis (Kelly & McNamara, 2010). In those experiments, participants viewed one object layout and later viewed another layout interspersed among the first. Manipulating layout 1 learning conditions (thereby manipulating the layout 1 reference frame) while holding layout 2 learning conditions constant revealed that the reference frame used to remember layout 2 depended on the reference frame used to remember layout 1, such that the entire environment was represented using a single reference frame. Using the same logic, an influence of visual cues (intended to influence visual reference frame selection) on the reference frame used to remember subsequently touched objects would indicate cross-sensory reference frame transfer and support the common reference frame hypothesis.

2. Experiment 1

Participants studied two objects through vision and then studied seven additional objects through touch. Visual cues were manipulated across participants during visual learning, whereas haptic learning conditions were held constant to observe the effects of visual reference frame manipulation.

2.1. Method

2.1.1. Participants

Twenty men and 12 women (average age: 20.2 years) participated for course credit.

2.1.2. Stimuli and design

Stimuli consisted of a three-by-three object grid (Fig. 1) centered on a round table (54 cm diameter). Objects were separated by a minimum of 18 cm. Three parallel black stripes (2.5 cm wide, separated by 18 cm) were drawn on the table, which was centered within a 3.9 × 4.1 m room with the stripes parallel to two room walls.

Two objects (Fig. 1, open circles) were studied visually, first from 0° and then from 315° (perspective is defined relative to the object layout). A single viewing order was used because reference frame selection typically occurs from views aligned with environmental axes, regardless of order (Shelton & McNamara, 2001a). Seven new objects (Fig. 1, filled circles) were then added to the table, and all nine objects were studied through touch from 315°. Visual axes (stripes and room walls) were aligned with the 315° haptic learning perspective (vision–touch aligned condition, Fig. 1 left) or misaligned with the haptic learning perspective (vision–touch misaligned condition, Fig. 1 right), and alignment was manipulated between participants. Fig. 2 shows a participant studying through touch from 315° in the vision–touch misaligned condition.

Participants later performed JRD in which they imagined standing at one object, facing a second object, and pointed toward a third object from that perspective. Participants imagined eight perspectives spaced every 45° from

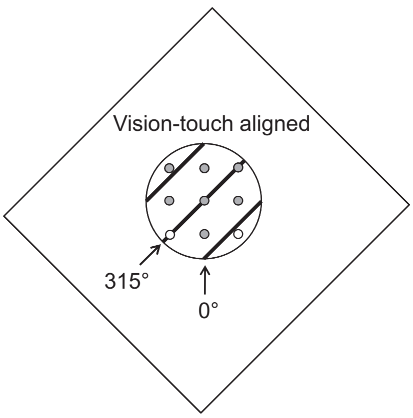

Fig. 1. Object layouts used in Experiments 1 and 2. In Experiment 1, participants studied two objects visually (open circles) from 0° and 315° before studying the same two objects plus seven new objects (filled circles) through touch from 315°. In Experiment 2, participants viewed the environment from 0° and 315° before studying all nine objects (open and filled circles) exclusively through touch. Visual environmental cues defined by the table stripes and room walls were either aligned (left panel) or misaligned (right panel) with the 315° haptic learning perspective. Actual objects used: (top row) battery, basket, apple, (middle row) slinky, tape, cup, (bottom row) stapler, candle, car.

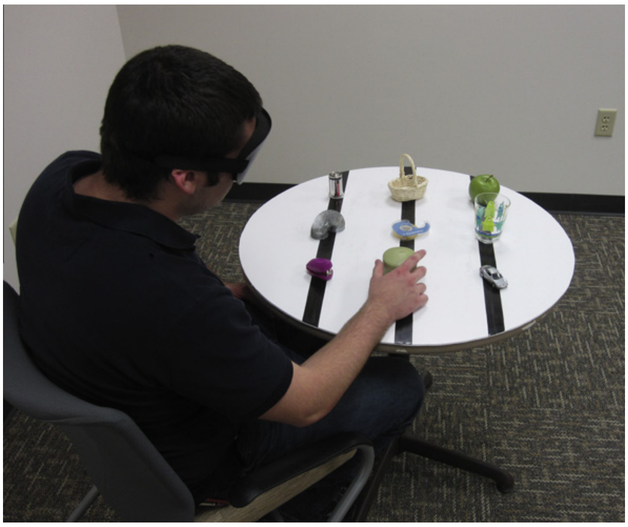

Fig. 2. Photograph of a participant studying objects through touch from the 315° haptic learning perspective in the vision–touch misaligned condition.

0° to 315°, and perspective was manipulated within participants. JRD objects came from the seven objects learned through touch; visually-studied objects were never tested. For each imagined perspective, six trials required egocentric pointing directions of 45°, 90°, 135°, 225°, 270° and 315°. Participants completed 48 trials in a random order.

Dependent measures were pointing error (absolute difference between the correct direction and the pointing response) and latency (elapsed time between trial presentation and pointing response). Vizard software (WorldViz, Santa Barbara, CA) presented JRD and recorded pointing data.

2.1.3. Procedure

Blindfolded participants were led into the learning environment, which contained two objects on the table. Participants were led to the 0° position, lifted their blindfolds, and began studying visually. After 20 s participants closed their eyes and pointed to the two objects in a random order. This study-test sequence was repeated until participants successfully pointed twice. Blindfolded participants were then led 45° clockwise to the 315° perspective where they repeated the visual study-test sequence before replacing the blindfold and sitting in a chair. Seven new objects were then added among the two previously viewed objects. The experimenter guided the blindfolded participant's right hand to each object on the table: first to the two previously viewed objects and then to the seven new objects in a random order. Participants then studied for 60 s by freely exploring using their right hand before pointing to each object in a random order. The study-test sequence was repeated until participants successfully pointed twice.

Participants were led to another room to perform JRD, which appeared as sentences on a computer monitor. Participants pointed by moving a joystick. Responses were recorded when the joystick was deflected by 30° from vertical.

2.1.4. Analysis

Facilitated pointing from one or more imagined perspectives is considered evidence that the memory was stored using a reference frame parallel to the facilitated perspective(s) (Klatzky, 1998). The primary objective during analysis was to determine which experienced perspective (0° or 315°) corresponded to the reference frame used to remember the layout. Data were analyzed in omnibus ANOVAs followed by contrasts targeting the experienced perspectives.

2.2. Results

There was no indication of speed-accuracy tradeoff. Within-participant correlations between latency and error averaged 0.15 ($SD = .39$), significantly above zero [$t(31) = 2.12$, $p = .042$]. For brevity, we focus on angular errors, but all significant ANOVA main effects and interactions were also found in latencies, across both experiments.

Absolute pointing error (Fig. 3) was analyzed in a mixed-model ANOVA with terms for learning condition (vision–touch aligned or misaligned) and imagined perspective. A significant main effect of imagined perspective [$F(7, 210) = 6.46$, $p < .001$, $\eta_p^2 = .18$] was qualified by a significant interaction [$F(7, 210) = 3.37$, $p = .002$, $\eta_p^2 = .10$]. A significant interaction contrast indicated that participants in the vision–touch aligned condition performed better when imagining 315° compared to 0°, whereas participants in the vision–touch misaligned condition showed the opposite pattern [$F(1, 30) = 11.25$, $p = .002$, $\eta_p^2 = .27$]. Simple contrasts confirmed that performance was better from 315° than 0° in the vision–touch aligned condition [$F(1, 15) = 6.52$, $p = .022$, $\eta_p^2 = .30$], and better from 0° than 315° in the vision–touch misaligned condition [$F(1, 15) = 4.77$, $p = .045$, $\eta_p^2 = .24$].

Error patterns in both conditions display "sawtooth" patterns of facilitated performance on perspectives aligned with visually-defined axes [vision–touch aligned: $F(1, 15) = 22.39$, $p < .001$, $\eta_p^2 = .60$; vision–touch misaligned: $F(1, 15) = 9.26$, $p = .008$, $\eta_p^2 = .38$]. Furthermore, performance on perspectives aligned with visual axes degraded with increasing angular distance from the experienced view [vision–touch aligned: $F(1, 15) = 5.60$, $p = .032$, $\eta_p^2 = .27$; vision–touch misaligned: $F(1, 15) = 8.95$, $p = .009$, $\eta_p^2 = .37$].

2.3. Discussion

Visual environmental cues influenced reference frame selection when learning locations through touch, demonstrating cross-sensory reference frame transfer. According to our interpretation, reference frame selection during visual learning was influenced by the orientation of the table stripes and room walls. Similar to results of Shelton and McNamara (2001a), participants selected a reference frame from the experienced perspective aligned with visual environmental cues: participants in the vision–touch aligned condition established a reference frame along the 315–135° axis and the orthogonal 45–225° axis, whereas participants in the vision–touch misaligned condition established a reference frame along 0–180° and the

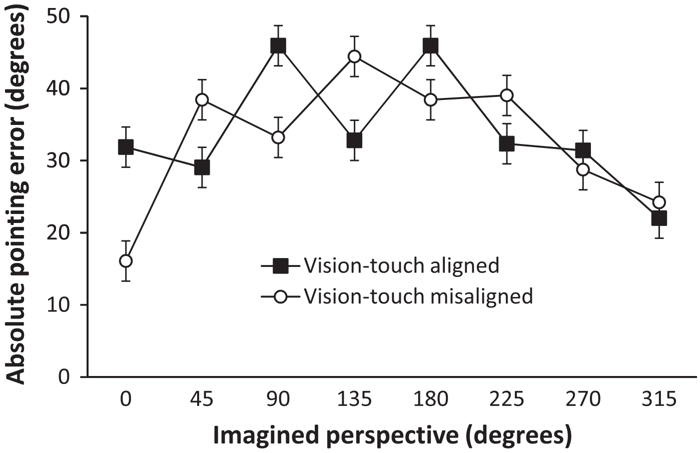

Fig. 3. Absolute pointing error as a function of imagined perspective and learning condition in Experiment 1. Error bars are standard errors estimated from the ANOVA.

orthogonal 90–270° axis. During subsequent haptic learning from 315°, participants in both conditions interpreted the touched layout in the context of the visually-established reference frame, resulting in the out-of-phase sawtooth patterns in Fig. 3. Furthermore, performance among perspectives aligned with visually-defined axes was best from the experienced view. In sum, visual cue manipulation influenced haptic reference frame selection, indicating that locations learned through different sensory modalities were organized within a common reference frame.

In addition to the influence of visual cues, performance was facilitated when imagining the haptic study perspective. In the vision–touch misaligned condition, performance was better when imagining the 315° perspective compared to 45°, which was equally misaligned with visual axes.[1] This indicates preserved memory from the haptic study perspective in addition to cross-sensory transfer.

In Experiment 1, visually-learned locations were present during haptic learning, which may have caused participants to remember touched objects in the context of the visually-determined reference frame. Experiment 2 explored the hypothesis that if locations learned through different modalities are characterized by a common reference frame, then cross-sensory transfer should occur without the presence of previously viewed objects during haptic learning.

3. Experiment 2

Unlike Experiment 1, participants in Experiment 2 were only incidentally exposed to visual cues during a JRD demonstration. Participants then studied all objects exclusively through touch. If the presence of visual objects during haptic learning is necessary for cross-sensory transfer, then reference frames used to remember touched objects should be unaffected by visual cue manipulation.

[1] $t(15) = 2.77$, $p = .014$.

3.1. Method

3.1.1. Participants

Twenty-eight men and 22 women (average age: 20.9 years) participated for course credit.

3.1.2. Stimuli, design, and procedure

Participants learned the same layout used in Experiment 1, except all objects were learned exclusively through touch. Participants were blindfolded and led to the 0° perspective, which contained no objects. Participants lifted their blindfolds and were given a 60 s JRD demonstration using three sample objects placed on the striped table. The demonstration was intended to draw attention to the visual environmental cues, and participants were told they did not need to remember the objects used in the demonstration. Demonstration objects were then removed and participants replaced their blindfolds and were led to the 315° perspective, where they were seated in a chair. Participants then lifted their blindfold again and were told that they would soon be touching objects placed on the table in front of them. After replacing the blindfold, nine objects were arranged on the table and participants studied them through touch until reaching criterion pointing performance. Testing was identical to Experiment 1, and JRD only included the seven objects tested in Experiment 1.

3.2. Results

There was no indication of speed-accuracy tradeoff. Within-participant correlations between response latency and error averaged 0.14 ($SD = .31$), which was significantly above zero [$t(49) = 3.07$, $p = .004$]. For brevity we focus on angular errors.

Absolute pointing error (Fig. 4) was analyzed in a mixed-model ANOVA with terms for learning condition and imagined perspective. A main effect of imagined perspective [$F(7,336) = 3.14$, $p = .003$, $\eta_p^2 = .06$] was qualified by a significant interaction [$F(7,336) = 2.88$, $p = .006$, $\eta_p^2 = .06$]. The interaction contrast between imagined per-

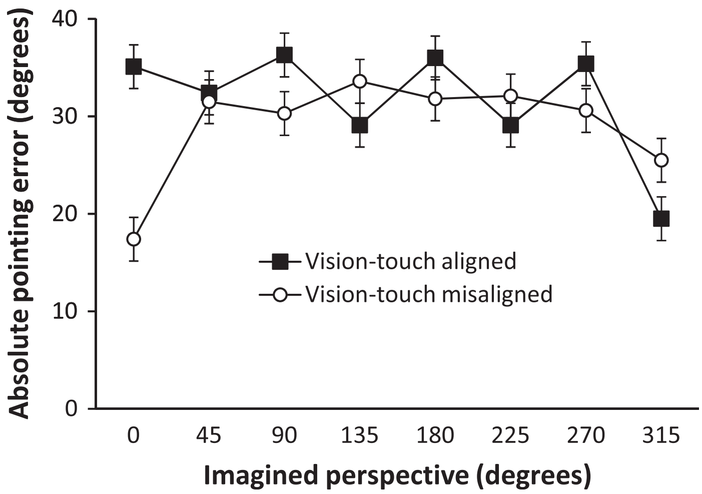

Fig. 4. Absolute pointing error as a function of imagined perspective and learning condition in Experiment 2. Error bars are standard errors estimated from the ANOVA.

spective (0° and 315°) and learning condition was significant [$F(1, 48) = 15.86$, $p < .001$, $\eta_p^2 = .25$]. Participants in the vision–touch aligned condition performed better when imagining 315° than 0° [$F(1, 24) = 19.99$, $p < .001$, $\eta_p^2 = .45$]. Participants in the vision–touch misaligned condition were more accurate from 0° than 315°, although that difference did not reach significance [$F(1, 24) = 2.82$, $p = .11$].

Sawtooth patterns indicating facilitated performance for perspectives aligned with visually-defined axes reached significance only in the vision–touch aligned condition [$F(1, 15) = 11.39$, $p = .002$, $\eta_p^2 = .12$]. Furthermore, performance on perspectives aligned with visual axes degraded with increasing angular distance from the experienced view [vision–touch aligned: $F(1, 15) = 11.93$, $p = .002$, $\eta_p^2 = .33$; vision–touch misaligned: $F(1, 15) = 23.27$, $p < .001$, $\eta_p^2 = .49$].

3.3. Discussion

Experiment 2 demonstrated that the presence of visual objects during haptic learning is not necessary for cross-sensory transfer. Exposure to visual environmental cues during a demonstration caused participants to select a reference frame aligned with environmental axes. Participants then interpreted the touched objects within the context of that reference frame, and subsequent retrieval was best from perspectives aligned with the visually-acquired reference frame.

Sawtooth patterns indicating facilitated performance on non-experienced perspectives aligned with visually-defined axes were less pronounced than in Experiment 1, only reaching significance in the vision–touch aligned condition. Incidental exposure to visual cues may be less salient than when visual learning is explicitly required, but this does not explain the seemingly greater attenuation in the vision–touch misaligned condition.

Unlike Experiment 1, there was little preserved memory from the haptic study perspective. In the vision–touch misaligned condition, performance was no different when imagining the 315° perspective (the haptic study perspective) compared to 45°, which was equally misaligned with visual axes.[2]

4. General discussion

This project investigated whether locations learned through different senses can be organized within a common reference frame rather than multiple modality-specific reference frames. Results indicate that locations from different modalities can be integrated by demonstrating cross-sensory reference frame transfer. Participants established a reference frame on the basis of visual cues present while visually studying objects (Experiment 1) or while viewing a task demonstration (Experiment 2), and later learned objects through touch. Manipulation of alignment between the visual reference frame and haptic study perspective indicated that participants remembered touched objects within the visually-defined reference frame.

In addition to the influence of visual cues, performance was facilitated when imagining the haptic study perspective in the vision–touch misaligned condition, although this trend only reached significance in Experiment 1. Preserved memory from the haptic study perspective is similar to results of Shelton and McNamara (2001a, Experiment 5) showing facilitated performance from multiple learning views in the presence of competing environmental axes. The authors interpret this as evidence for multiple representations of the space.

One possible account of these findings is that participants integrated locations from different modalities into a single representation, which fits well with neuroscientific evidence that brain regions associated with different senses converge onto multisensory brain areas and even connect within sensory-specific cortices (Amedi, von Kriegstein, van Atteveldt, Beauchamp, & Naumer, 2005;

[2] $t(24) = 1.68$, *ns*.

Macaluso & Driver, 2005). Locations learned in the same environment through different senses share the common purpose of supporting spatial behaviors within the remembered space. If locations learned through different senses were represented within different reference frames, then cross-modal spatial judgments would require mental rotation to align those reference frames. Representing locations learned through different senses within a common reference frame benefits spatial behavior by minimizing transformation costs.

The current results diverge from previous findings that locations learned through vision and proprioception resulted in separate reference frames (Yamamoto & Shelton, 2005). One explanation is that participants in that study maintained a constant facing direction when walking to each location during proprioceptive learning, which may have resulted in new memories from that perspective. Hand movements during free-exploration in the current experiments might have been consistent with the visually-defined reference frame, similar to eye movements (Mou, Liu, & McNamara, 2009). Furthermore, the layout in the current studies was smaller than that used by Yamamoto and Shelton, and scale might influence reference frame selection. Finally, participants in Yamamoto and Shelton's experiments never viewed the proprioceptive study perspective, whereas participants in the current experiments learned visual objects from the haptic learning perspective. Careful control of these differences could elucidate the necessary conditions for cross-sensory transfer.

Although our findings indicate that locations from different modalities were integrated into a common representation, they do not allow inferences about the representational format. One possibility is that locations learned through touch were recoded into a visual representation. Research by Shelton and McNamara (2001b) on multimodal learning supports this recoding hypothesis. Participants viewed an object layout from one perspective and haptically reconstructed the layout from another perspective. Subsequent visual recognition of the layout was best from the reconstructed perspective, suggesting that locations learned through touch were recoded into a visual format. However, congenitally blind and sighted people exhibit equivalent spatial updating of locations learned nonvisually (Loomis, Lippa, Klatzky, & Golledge, 2002), indicating that spatial representations are not necessarily visual. One alternative to the recoding hypothesis is that the representation is amodal, not tied to any sensory modality (Bryant, 1997; Loomis, Klatzky, Avraamides, Lippa, & Golledge, 2007). Amodal representations would allow comparable retrieval irrespective of encoding modality, although neural traces of the learning modality may persist (Tlauka, Clark, Liu, & Conway, 2009).

This project advances our understanding of how reference frames influence multimodal spatial learning. Previous work has shown that visually-determined reference frames can provide scaffolding for remembering new visual locations (Kelly & McNamara, 2010). The current experiments extend those findings to encompass multimodal learning, and support the hypothesis that spatial memories learned through different senses can be organized around a common reference frame rather than multiple modality-specific reference frames.

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