Incidental encoding of enclosure geometry does not require visual input: evidence from blindfolded adults

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Abstract Although spatial orientation with respect to the geometric properties of an environment appears to be an ability shared across various species, debate remains concerning potential similarities and differences with respect to the underlying mechanism(s). One prominent theoretical account of orientation with respect to the environment suggests that participants match visual memories to their current visual perception and navigate to reduce the discrepancy between the two. We tested whether visual input was necessary to incidentally encode the geometric properties of an environment, by training disoriented and blindfolded adult participants to search by touch for a target object hidden in one of four locations, marked by distinctive textural cues, located in the corners of a rectangular enclosure. Following training, we removed the distinctive textural cues and probed the extent to which the participants had learned the geometry of the enclosure. Even in the absence of vision and unique textural cues, search behavior was consistent with evidence for the encoding of enclosure geometry. A follow-up experiment in which participants were trained in a rectangular enclosure but were tested in a square enclosure provided converging evidence that search behavior was influenced by the geometric properties of the enclosure. Collectively, these results suggest that even in the absence of vision, participants incidentally encoded the geometric properties of the enclosure, indicating that visual input is not required to encode the geometric properties of an environment.

Determination of current position with respect to the environment is critical for navigation (Gallistel, 1990). One way that researchers have investigated the ability to determine one's current position with respect to the environment has involved placing disoriented participants into a rectangular enclosure (see Cheng, Huttenlocher, & Newcombe, 2013; Cheng & Newcombe, 2005). When trained to approach a unique visual cue located in one corner, participants are equally likely to search at above-chance levels in this trained corner and in its 180° rotational equivalent upon subsequent removal of the visual cue (Cheng et al., 2013; Cheng & Newcombe, 2005). This "rotational error" phenomenon has been interpreted as evidence for incidental encoding of the geometric properties of an enclosure (Cheng, 1986).

Despite cross-species evidence for the rotational-error phenomenon, debate remains concerning the underlying mechanism(s) (Cheng et al., 2013; Cheng & Newcombe, 2005). View-based matching theories have emerged to suggest that orientation (and navigation) is accomplished by storing a visual memory of the target location and maneuvering to reduce the discrepancy between this visual memory and the current visual perception (Cheng, 2012; Pecchia, Gagliardo, & Vallortigara, 2011; Pecchia, & Vallortigara, 2010; Stürzl, Cheung, Cheng, & Zeil, 2008). View-based matching theories have gained recent prominence because of their capability to explain the relatively complex spatial behavior of ants via relatively simply computational processes (for reviews, see Cheng, 2008, 2012; Pecchia & Vallortigara, 2010), and this empirical support, coupled with the theory's theoretical appeal, has raised questions regarding the extent to which view-based matching theories can explain the spatial behavior of species other than insects.

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Although recent evidence suggests that view-based matching theories may be able to explain the spatial behavior of pigeons (e.g., Pecchia et al., 2011; Pecchia & Vallortigara, 2012), such theories appear insufficient to account for human spatial orientation (e.g., Bodily, Eastman, & Sturz, 2011; Lee & Spelke, 2011; Sturz, Gurley, & Bodily, 2011). To date, however, studies providing evidence against view-based matching theories of human spatial orientation appear susceptible to interpretations based on matching visual memories to current visual perception. One potential way to directly test such a view-based matching theory would be to eliminate the possibility of visual encoding, and recently Sturz et al. (2013) trained disoriented and blindfolded participants to search by touch for a target object hidden on top of one of four discrete landmarks, each marked with a distinctive textural cue arranged in a rectangular array. After reaching a training criterion, the textural cues were removed to probe the extent to which participants had learned the geometry of the landmark array. In the absence of vision and the distinct textural cues, participants responded to the correct and rotationally equivalent locations at above-chance levels.

Sturz et al. (2013) suggested that their results provided evidence for incidental encoding of the geometric properties of the landmark array via touch in the absence of vision, and they argued that this obtained evidence could not be undermined by appealing to a strict view-based matching account of orientation (Pecchia et al., 2011; Pecchia & Vallortigara, 2010; Stürzl et al., 2008). Their logic was that strict view-based matching necessarily requires visual input in order to encode a visual memory, to have access to current visual perception, and to reduce any discrepancy between the current visual perception and any visual memory. Sturz et al. (2013) argued that by explicitly prohibiting the use of vision during the orientation task, they eliminated the possibilities of encoding a visual memory, having access to current visual perception, and/or reducing the discrepancy between a current visual perception and a visual memory.

Although the results of Sturz et al. (2013) suggest that visual input is not required for the incidental encoding of the geometric properties of a *landmark array*, research on encoding of environmental geometry has been conducted almost exclusively in enclosed search spaces (for reviews, see Cheng et al., 2013; Cheng & Newcombe, 2005). As a result, it remains an open question whether incidental encoding of *enclosure geometry* requires visual input. Given the theoretical importance of such an open question, coupled with methodological and empirical limitations of the results of Sturz et al. (2013), we conducted a replication and extension of Sturz et al. (2013) in an enclosed search space. With respect to theoretical importance, such an open question appears to have comparative implications for illuminating potential similarities and differences with

respect to the underlying mechanism of geometric encoding, illuminating potential similarities and differences in the nature of the geometric information acquired through visual versus haptic exploration, and, ultimately, illuminating the extent to which types of spatial information acquired through different sensory modalities are functionally equivalent (see Giudice, Betty, & Loomis, 2011; Loomis & Klatzky, 2008). With respect to methodological limitations, the evidence for incidental encoding of the geometric properties of a landmark array that was reported by Sturz et al. (2013) was obtained in a relatively small array (i.e., 135 × 60 cm), and the landmarks themselves were relatively close to the participants' starting position (i.e., within ~60 cm). As a result, geometrically correct locations could have been learned by associating a relatively simple left or right response based on differences in proprioceptive feedback provided by simultaneous exploration of the landmarks, rather than by learning the geometric properties of the landmark array. With respect to empirical limitations, the design of Sturz et al. (2013) lacked an explicit test in an array of uninformative geometry (e.g., a square) to rule out the possibility of the use of cues internal or external to the enclosure other than those of the geometric properties.

In the present experiments, we utilized an enclosed search space for training and testing that was of a size to reduce an ability to explore two landmarks simultaneously, and we included a follow-up control condition in which participants were trained in a rectangular enclosure and tested in a square enclosure. More specifically, we trained participants who were both disoriented and blindfolded to search by touch for a target object hidden on top of one of four discrete landmarks, each marked with a distinctive textural cue, arranged in a rectangular array (see Fig. 1). Importantly, the landmarks were connected by polyvinyl chloride (PVC) pipe to form an enclosure. After participants reached a specified training criterion, we removed the distinctive textural cues and probed the extent to which they had learned the geometry of the enclosure. Although all participants were trained in a rectangular enclosure, in Experiment 1 we tested participants in the same rectangular enclosure experienced during training, whereas in Experiment 2 we tested participants in a novel square enclosure.

If participants are capable of incidentally encoding enclosure geometry via touch, in the absence of vision and of the ability to explore two landmarks simultaneously, the participants in Experiment 1 should respond to the correct and rotationally equivalent locations at above-chance levels in the absence of distinct textural cues. In contrast, the participants in Experiment 2, tested in a square enclosure, should respond equally to all four locations because of an absence of informative enclosure geometry.
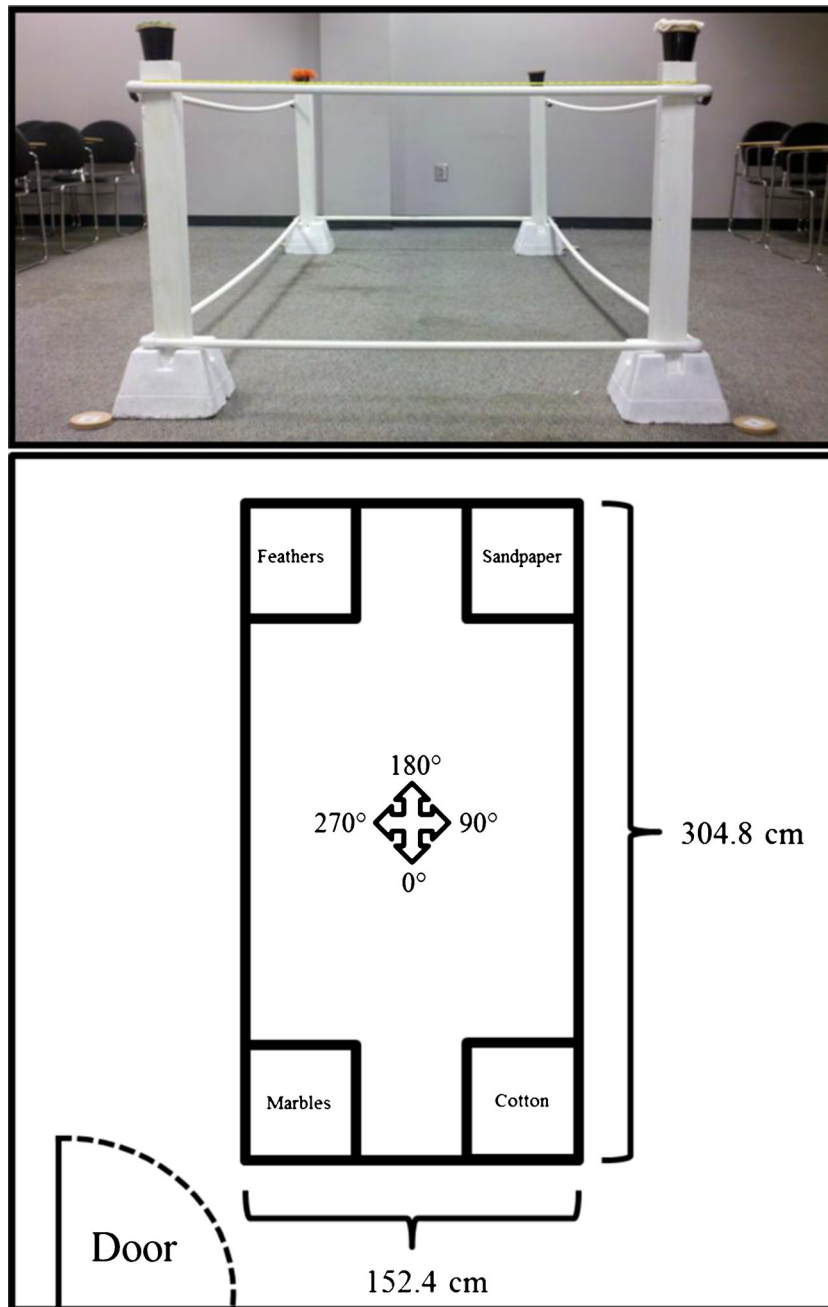
Fig. 1 Image (top) and schematic (bottom) of the rectangular enclosure, textures, and experimental room. For illustrative purpose, the start position is marked. Please note that the schematic is not to scale. Please also note that textures were present during all training trials but were absent during the testing trial (see the text for details).

Experiment 1

Method

Participants

A group of 16 undergraduate students served as participants (eight males, eight females). All of the participants provided dominant hand information (88 % right-handed, 12 % left-handed), had normal sensorimotor abilities, and received extra credit or participated as part of a course requirement.

Apparatus and stimuli

The experimental events occurred in a room measuring ~12 × ~11 m (see Fig. 1). Four identical wooden posts served as landmarks. Each post measured 9.00 (length) × 9.00 (width) × 92.00 (height) cm and was affixed to a concrete Dek-Block that measured 27.8 × 27.8 cm at the base and 20.1 × 20.1 cm at the

top (height of 20.2 cm). The total height of each landmark was 112 cm. Each post was sanded and painted white. Two rope hooks were affixed to each post (one at bottom and one at top), and these held two boundaries created around the perimeter of the landmarks. The boundaries were PVC pipe (diameter of 1.9 cm) with 90° PVC elbow connectors and were located 22.9 and 11.8 cm from the floor. A small metal container [10.2 (opening diameter) × 7.6 (bottom diameter) × 9.5 (height) cm] was affixed to the top of each landmark. The lid of each container was removable. During training (see below), the lids were covered with four distinct textures (clockwise from top left in Fig. 1: feathers, sandpaper, cotton, and marbles). The textures remained in these locations for the duration of training (see below). During testing (see below), the textured lids were replaced with four identical blank (cardboard-only) lids. A wooden block [5.08 (length) × 2.22 (width) × 2.54 (height) cm] served as the target object. The four posts were arranged in a rectangular array that measured 304.8 × 152.4 cm (see Fig. 1).

Procedure

In a separate room, participants were informed that they would first touch four textures located on top of wooden posts. After touching each texture, they would search for a small wooden block hidden in a small container below each texture. Participants were informed that they would select a container by removing the lid and inserting their hand into the container. They were also informed that these activities would occur while blindfolded. Finally, the participants were informed that they would continue the experiment until they had located the wooden block six times in a row on their first choice (i.e., six consecutive correct first choices) or until 45 min had elapsed. Participants were then blindfolded and led into the experimental room containing the rectangular enclosure.

Training A randomly selected landmark (including its textured lid) was designated as the rewarded corner, which contained the target object for that participant for the duration of training. The wooden block was placed in the container of the designated trained corner. Equal numbers of males and females were trained at each corner (and texture), resulting in each of the four textural cues serving as the rewarded corner for two males and two females.

Prior to the start of each trial, the experimenter led the blindfolded participants to the center of the enclosure and attempted to disorient them. The experimenter physically spun participants in circles in the center of the enclosure in either a clockwise or a counterclockwise direction while the experimenter rotated around the participant in the opposite direction. Each participant's spinning direction was randomized, and the experimenter terminated the participant's spin facing a random direction from 0° to 270°, in increments of 90°, for each trial (see Fig. 1). Participants then touched all of the textures

and began their search for the target object. They searched until they had located the target object.

After participants had located the target object, the experimenter retrieved the target and led the participant back to the start position. The experimenter then inserted the wooden block back into the trained location and returned the textured lids to their respective locations. Placement of the lids at their original locations occurred in random order from trial to trial, to prevent learning of location on the basis of sound. The disorientation procedure was repeated, and the participants' spin was terminated facing a random direction. This process was repeated for each trial. Each time that a participant located the target object on his or her first choice, the experimenter verbally informed the participant of his or her current consecutive correct first choices. Once participants had located the target object five consecutive times on their first choice, testing began. Note that participants believed that they were required to find the target object once more on their first choice when testing began.

Testing The testing consisted of one trial and was conducted in a manner identical to the training, with the exception that the textured lids were replaced with blank lids (cardboard only) when placed on top of the containers. As a result, the locations were devoid of all textural cues that had been present during training. Moreover, the target object was absent. After being spun in circles that terminated facing a random direction (as in training), participants began their search (as in training). To be consistent with Sturz et al. (2013), we terminated the search process after each participant's fifth search in the test enclosure.

Results and discussion

Training

All participants met the training criterion of five consecutive correct first choices and learned to use their distinctive textural cue to locate the target object (trials to reach criterion, $M =$ 10.44, $SEM = 0.95$). We analyzed the extent to which first choices were correct for the first six trials of training (trials that allowed for the inclusion of all participants) by creating three, two-trial blocks. A two-way mixed analysis of variance (ANOVA) on mean proportions of correct first choices, with Gender (male, female) and Block (1–3) as factors, revealed only a main effect of block, $F(2, 28) = 8.28$, $p < .01$, $\eta_p^2 = .37$. Neither the effect of gender nor the interaction was significant, $Fs < 1.2$, $ps > .32$. Post-hoc tests revealed that the mean proportion of correct first choices for Block 3 ($M = .69$, $SEM = .11$) was significantly greater ($ps < .05$) than those of Block 1 ($M = .22$, $SEM = .08$) and Block 2 ($M = .38$, $SEM = .10$), but Blocks 1 and 2 were not significantly different from each other ($p = .2$). The mean proportions of correct first choices for Blocks 1 and 2 were also not significantly different

from chance (i.e., .25), one-sample *t* tests, *t*s(15) < 1.3, *p*s > .21, but the mean proportion of correct first choices for Block 3 was significantly greater than chance, one-sample *t* test, *t*(15) = 3.96, *p* < .01. These results suggest that participants rapidly learned to utilize their respective distinctive textural cue to determine the correct location at above-chance levels.

Testing

For testing, we isolated our analysis to the allocation of first choices to the four locations. Consistent with previous research (e.g., Cheng & Newcombe, 2005), locations were defined as to whether they were (1) correct (where the rewarded texture would have been), (2) near (geometrically incorrect location closest to the correct location), (3) far (geometrically incorrect location farthest from the correct location), and (4) rotationally equivalent (180° equivalent of the correct location). Even though the rewarded location was counterbalanced across participants, choices were transformed for data presentation purposes so that, for all participants, the rewarded (i.e., trained) location was located at the top left location shown in Fig. 2.

First choice [1] We analyzed participants' first choices (Fig. 2, left). Importantly, the proportions of first choices to the correct and the rotationally equivalent locations were not significantly different from each other, binomial test, *z* = 0.00, *p* = 1.0, and the total proportion of first choices (i.e., .88) to these geometrically correct locations was significantly above chance (i.e., .5), $\chi^2(1, N = 16) = 9.00$, *p* < .01.[2] This suggests that in the absence of the distinctive textural cues, participants were able

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[1] The allocation of the mean proportions of all five test choices was consistent with the distribution of first choices. The mean proportions of all five choices to the correct and rotationally equivalent locations did not differ from each other. This was confirmed by a two-way mixed ANOVA on the mean proportions of all five choices, with Gender (male, female) and Location Type (correct, rotational equivalent) as factors, which revealed no main effects or interaction, *F*s < 4.6, *p*s > .05. The mean proportion of choices allocated to these geometrically correct locations (*M* = .56, *SEM* = .02) was significantly greater than chance (i.e., .5), one-sample *t* test, *t*(15) = 3.1, *p* < .01. Although the mean proportion of all five choices to the geometrically correct locations may seem relatively low, no participant made more than one repeat choice to a previously chosen location. As a result, the maximum possible value of the proportion of all five choices to geometrically correct locations was .6 (3/5). The mean proportion of all five choices to the geometrically correct locations did not differ from this maximum possible value, one-sample *t* test, *t*(15) = 1.86, *p* = .08.
[2] It is worth noting that of the 14 participants who selected a geometrically correct location (i.e., correct or rotationally equivalent) for the first choice, seven (i.e., .5) selected the other geometrically correct location on the second choice; however, this allocation of responses for the second choice was not significantly different from would be expected on the basis of chance (i.e., .33), $\chi^2(2, N = 14) = 1.86, p = .39$. This suggests that after failing to find the target object on the first choice, participants selected the next search location in a random fashion.

to utilize the geometric properties of the enclosure to immediately guide their search behavior; however, they were unable to disambiguate the correct from the rotationally equivalent location.

To ensure that only the geometric properties of the enclosure were responsible for guiding search behavior to the correct and rotationally equivalent locations (as opposed to cues other than the geometric properties of the enclosure), we conducted a follow-up experiment in which we trained new participants in the rectangular enclosure utilized in Experiment 1; however, we tested these participants in a square enclosure instead of the rectangular enclosure. If informative enclosure geometry was responsible for guiding participants' search behavior in Experiment 1, the participants in Experiment 2 should respond equally to all four locations in the absence of informative enclosure geometry. As a result, participants should allocate responses to the geometrically correct locations at chance levels (i.e., .5).

Experiment 2

Method

Participants

A group of 16 undergraduate students (different from those in Exp. 1) served as participants (eight males, eight females). All participants provided dominant hand information (94 % right-handed, 6 % left-handed), had normal sensorimotor abilities, and received extra credit or participated as part of a course requirement.

Apparatus, stimuli, and procedure

The apparatus, stimuli, and procedure were identical to those aspects of Experiment 1, with the exception that prior to the test trial, the landmarks and enclosure were modified such that they formed a square enclosure (152.4 × 152.4 cm).

Results and discussion

Training

All participants met the training criterion of five consecutive corrective first choices and learned to use their distinctive textural cue to locate the target object (trials to reach criterion, *M* = 9.5, *SEM* = 0.76). As in Experiment 1, we analyzed the extent to which first choices were correct for the first six trials of training

Allocation of Choices During Testing Following
Training in a Rectangular Enclosure
(in the absence of textural cues)

Experiment 1

Proportion of First
Choices

Experiment 2

Proportion of First
Choices
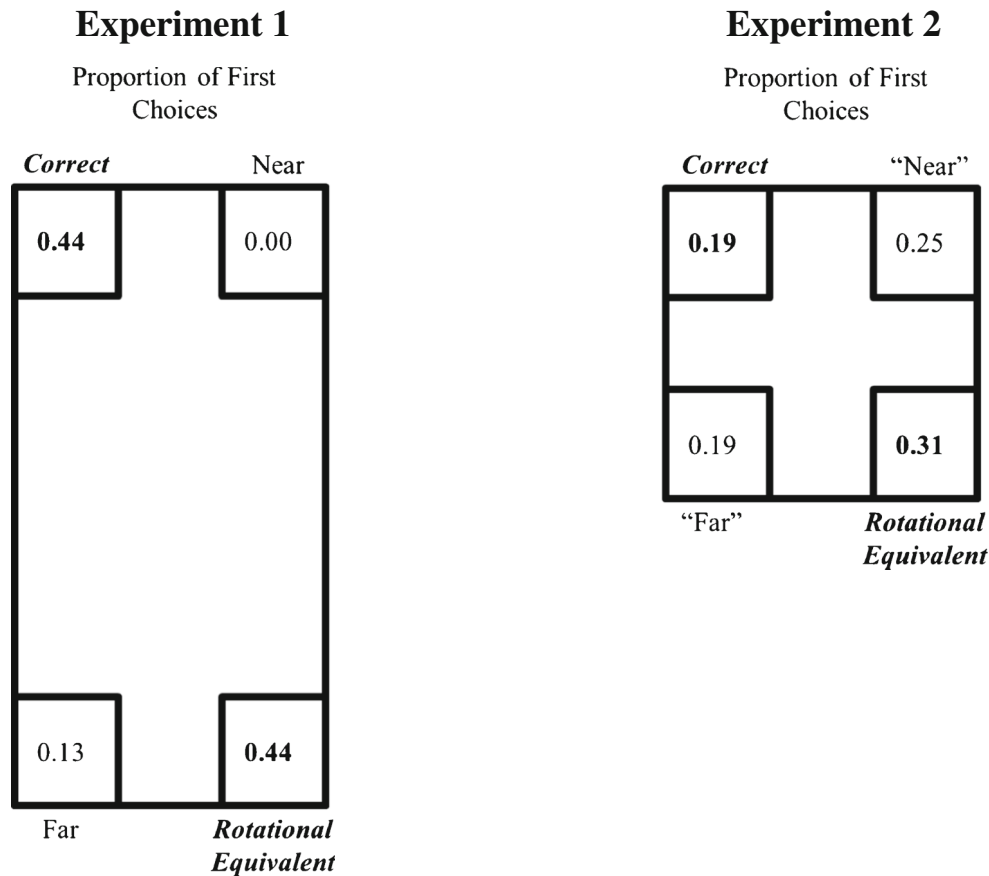
Fig. 2 (Left) Allocation of the proportion of first choices to each location during testing in the rectangular enclosure of Experiment 1. (Right) Allocation of the proportion of first choices to each location during testing in the square enclosure of Experiment 2. Please note that choices were transformed for data presentation purposes, so that in the figure the rewarded (i.e., trained) location is located at the top left location for all participants, even though the rewarded location was counterbalanced across participants (see the text for details). The correct and rotationally equivalent locations are **bolded** and *italicized* to illustrate the geometrically correct locations.

by creating three, two-trial blocks. A two-way mixed ANOVA on mean proportions of correct first choices, with Gender (male, female) and Block (1–3) as factors, revealed only a main effect of block, $F(2, 28) = 12.47$, $p < .001$, $\eta_p^2 = .47$. Neither the effect of gender nor the interaction was significant, $Fs < 1.32$, $ps > .28$. Post-hoc tests revealed that the mean proportions of correct first choices for Block 2 ($M = .53$, $SEM = .10$) and Block 3 ($M = .66$, $SEM = .12$) were significantly greater ($ps < .01$) than that for Block 1 ($M = .13$, $SEM = .06$), but Blocks 2 and 3 were not significantly different from each other ($p = .32$). The mean proportion of correct first choices for Block 1 was significantly less than chance (i.e., .25), one-sample t test, $t(15) = 2.24$, $p < .05$, and the mean proportions of correct first choices for Blocks 2 and 3 were significantly greater

than chance, one-sample t tests, $ts(15) > 2.91$, $ps < .05$. As with Experiment 1, these results suggest that participants rapidly learned to utilize their respective distinctive textural cue to determine the correct location at above-chance levels.

Testing

As with Experiment 1, we analyzed the testing data through the allocation of choices to the four locations. We again defined locations as to whether they were (1) correct, (2) "near," (3) "far," or (4) rotationally equivalent. "Near" and "far" are in quotes because all locations were equidistant in the square enclosure. Choices were again transformed for data presentation purposes so that for all

participants, the rewarded location is located at the top left location shown in Fig. 2.

First choice [3] As with Experiment 1, we isolated the analysis to participants' first choices (Fig. 2, right). Importantly, the distribution of choices to the four locations was not significantly different from what would be expected by chance (i.e., .25), $\chi^2(3, N = 16) = 0.5$, $p = .92$. As importantly, the proportions of first choices to the correct and the rotationally equivalent locations were not significantly different from each other, binomial test, $z = -1.21$, $p = .23$, and the total proportion of first choices (i.e., .56) to these "geometrically correct" locations was not significantly above chance (i.e., .5), $\chi^2(1, N = 16) = 0.25$, $p = .62$. This suggests that in the absence of the distinctive textural cues and informative enclosure geometry, participants were unable to distinguish the four locations from each other.[4]

General discussion

The results from both experiments indicated that disoriented and blindfolded participants were capable of rapidly learning to use a unique texture to determine the location of a target object. Our testing results indicated that in the absence of the unique texture, the participants in Experiment 1 allocated responses at above-chance levels to the trained and rotationally equivalent locations, whereas participants in Experiment 2 allocated responses equally to all four locations. These results suggest that the participants in Experiment 1 incidentally encoded the geometric properties of the rectangular enclosure even in the absence of vision, and were able to utilize this geometric information to guide their search in the absence of unique textural cues. In contrast, in the absence of informative enclosure geometry, the participants in Experiment 2 were unable to distinguish the four locations from each other.

Of methodological importance, our use of a larger search space than that of Sturz et al. (2013) reduces the possibility

that participants learned the locations by associating a relatively simple left or right response based on differences in the proprioceptive feedback provided by simultaneously exploration of two landmarks. Of empirical importance, our inclusion of an appropriate control condition (i.e., those trained in a rectangular enclosure and tested in a square enclosure) eliminates the possibility of orientation by cues other than enclosure geometry. Of theoretical importance, the evidence for incidental encoding of the geometric properties of a landmark array found by Sturz et al. (2013) generalized to an enclosed search space, providing additional evidence against view-based matching accounts of human spatial orientation and strengthening claims regarding the similarity of geometric information acquired through visual versus haptic exploration.

Although the exact mechanisms responsible for the present results remain unclear, we speculate that incidental encoding of geometric properties may be a characteristic shared across multiple sensory modalities, such that extraction of geometric cues occurs irrespective of input modality. Specifically, it may be that exploration of an environment via vestibular, kinesthetic, and/or proprioceptive cues alone is sufficient for extraction of the geometric properties (e.g., symmetry axis) of an environment, in the same manner that visual cues alone are sufficient for extraction of the geometric properties of an environment. Such speculation is consistent with theoretical approaches that propose the functional equivalence of spatial representations, regardless of learning modality (e.g., Loomis & Klatzky, 2008; see also Giudice et al., 2011), as well as research regarding haptic object perception in which geometric properties such as distance, size, and curvature appear to be extracted from purely tactile input (e.g., Henriques & Soechting, 2003; Lederman & Klatzky, 2009). Such speculation also appears to be consistent with research regarding spatial reference frames in which spatial memories acquired through haptic cues are functionally equivalent to spatial memories acquired through visual cues (e.g., Yamamoto & Philbeck, 2013) and spatial memories acquired through visual and haptic cues appear to be integrated into a common frame of reference (e.g., Avraamides, Sarrou, & Kelly, 2014; Kelly & Avraamides, 2011; Kelly, Avraamides, & Giudice, 2011).

We acknowledge that we are unable to rule out the possibility of the use of internally generated visual images (i.e., visual mental imagery) in the present set of experiments. Specifically, the possibility remains that participants created a visual memory of the target location via visual mental imagery during training. Such a memory based on visual mental imagery could be compared to any visual images created through visual mental imagery during real-time exploration of the environment. Although the viability of this visual mental imagery explanation would require additional empirical investigation (potentially with congenitally blind individuals), such an explanation may be capable of being incorporated into existing view-based matching theories of orientation

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[3] The allocation of the mean proportions of all five test choices was consistent with the distribution of first choices. Specifically, the mean proportions of all five choices to the correct and rotationally equivalent locations did not differ from each other. This was confirmed by a two-way mixed ANOVA on mean proportions of all five choices, with Gender (male, female) and Location Type (correct, rotational equivalent) as factors, which revealed no main effects or interaction, $Fs < 1.1$, $ps > .33$. The mean proportion of choices allocated to these "geometrically correct" locations ($M = .48$, $SEM = .03$) was not significantly greater than chance (i.e., .5), one-sample t test, $t(15) = 1.0$, $p = .33$. An across-experiment comparison of the mean proportions of all five choices to the geometrically correct locations revealed a significant difference, independent-samples t test, $t(30) = 2.73$, $p < .05$.

[4] An across-experiment comparison of first choices to the geometrically correct locations revealed a significant difference, binomial test, $z = 2.1$, $p < .05$.

and navigation, and may actually broaden their applicability to internally generated visual processing (see also Wystrach & Graham, 2012).

Regardless, our results indicate that encoding a visual memory, accessing current visual perception, and reducing discrepancy between a current visual perception and a visual memory are not required for adult participants to learn the geometric properties of an enclosure. Such results suggest that haptic cues alone are sufficient for the extraction of the geometric properties of an environment, and they appear consistent with emerging evidence against strict view-based matching theories of human spatial orientation (e.g., Bodily et al., 2011; Lee & Spelke, 2011; Sturz et al., 2013; Sturz et al., 2011). Future research may be able to utilize the present paradigm to continue comparative investigations of the potential similarities and differences with respect to the underlying mechanism(s) of geometric encoding, while simultaneously illuminating similarities and differences in the nature and functional equivalence of spatial information acquired through visual versus haptic exploration.

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