No evidence that consistent auditory cues facilitate learning of spatial relations among locations

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Abstract

Human participants searched in a dynamic three-dimensional computer-generated virtual-environment open-field search task for four hidden goal locations arranged in a diamond configuration located in a 5 × 5 matrix of raised bins. Participants were randomly assigned to one of two groups: Consistent or Inconsistent. All participants experienced 30 trials in which four goal locations maintained the same spatial relations to each other (i.e., a diamond pattern), but this diamond pattern moved to random locations within the 5 × 5 matrix from trial-to-trial. For participants in the Consistent group, each goal location within the pattern always provided a unique and consistent auditory cue throughout the experimental session. For participants in the Inconsistent group, the same distinct auditory cues were provided for each goal location; however, the locations of these auditory cues within the pattern itself were randomized from trial-to-trial throughout the experimental session. Results indicated that participants in both groups learned the spatial configuration of goal locations, but the presence of consistent auditory cues did not facilitate the learning of spatial relations among locations.

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An ability to learn spatial relations among locations permits an individual to locate objects in space relative to each other without reference to discrete visual landmarks or environmental geometry (see Brown, 2006a,b), and research suggests that both human infants and adults are capable of learning such spatial relations in the absence of discrete visual landmarks or environmental geometry (Mou and McNamara, 2002; Shelton and McNamara, 2001; Uttal and Chiong, 2004). Of theoretical interest is that this type of learning appears to be immune to competition from landmark learning (for a review, see Brown, 2006a,b). For example, participants trained in a spatial pattern learning task in the presence of visual cues showed no deficiency in their ability to learn the spatial relations among locations (as compared to a group trained in the absence of the cues) during a testing phase when cues were absent (Sturz et al., 2009). The presence of the visual cues during training did not overshadow learning about the spatial relations among goal locations, but the presence of these visual cues during training actually facilitated the learning of the spatial relations among locations in a subsequent testing phase.

More recent research regarding learning of spatial relations among locations has not only replicated these effects but also indicated that coincident visual cues are not required for the facilitation effect (Sturz et al., 2010). Perhaps more importantly, there is evidence that pattern learning is the processes that is facilitated by the visual cues (Sturz et al., 2010). Specifically, using a diamond configuration of four goal locations, participants trained in the presence of a single visual cue located at a non-goal location in the center of the pattern performed superior to those trained in its absence when the visual cue was removed during a subsequent testing phase. In addition, participants trained in the presence of this visual cue were shown to make fewer adjacent moves (i.e., moves that did not conform to the spatial configuration of goal location) and more diagonal moves (i.e., moves that conformed to the spatial configuration of goal locations) following the successful discovery of a goal location compared to participants in a group trained in the absence of the visual cue when the cue was removed during a subsequent testing phase.

Collectively, these results have been interpreted within models of spatial learning that suggest the certainty and variability of a spatial cue is encoded which affect its weighting relative to other spatial cues (e.g., Cheng et al., 2007; Newcombe and Ratiliff, 2007; Ratiliff and Newcombe, 2008). In the pattern learning studies to date, the number of reliable spatial cues present on any given trial could potentially explain the facilitation effect in the presence of visual cues. For example, the pattern could be considered one spatial cue and the visual cues another. As a result, participants trained in the presence of visual cues would have an additional spatial cue...
available during training to assist in the learning of spatial relations among locations.

The bulk of research on spatial learning has focused on visual spatial cues (for a review, see Brown and Cook, 2006), and to our knowledge, these aforementioned weighting models do not differentiate between cue modality. Specifically, these models do not appear to specify that spatial cues in one modality should be preferred over spatial cues in another; however, evidence suggests that when visual and spatial cues conflict for a spatial location that participants are able to integrate both cues – with a slight reliance on visual over spatial cues (see Battaglia et al., 2003). Given that multiple cues in multiple modalities are simultaneously available to moving organisms, we examined the effect of auditory cues on learning spatial relations among locations and, by extension, the extent to which cue modality influences spatial learning. Specifically, we investigated to what extent auditory cues can influence spatial pattern learning. To assess the influence of auditory cues on the learning of spatial relations among locations, one group of participants (Consistent group) was presented a diamond spatial configuration, and selection of a goal location for participants in this group resulted in one of four distinct auditory cues such that each of the four locations within the pattern itself always provided a unique and consistent auditory cue throughout the experimental session. Another group of participants (Inconsistent group) was presented the same diamond spatial configuration and the same distinct auditory cues for selection of a goal location; however, the locations of these auditory cues within the pattern itself were randomized from trial-to-trial throughout the experimental session. As a result, participants in the Consistent group could utilize the auditory cues to determine their specific location within the diamond configuration whereas those in the Inconsistent group could not.

From a weighting of spatial cues perspective, the Consistent group would have two types of reliable and stable cues (i.e., the pattern and consistent auditory cues) whereas the Inconsistent group would have only one type of reliable and stable cue (i.e., the pattern). With respect to the number of spatial cues present, these assumptions provide a prediction of increased performance in the presence of more reliable and stable types of spatial cues. Within the context of the present experiment, these assumptions translate to a prediction that participants in the Consistent group should perform superior relative to those of the Inconsistent group with respect to measures of spatial pattern learning. Specifically, with the diamond pattern used in this experiment, learning of the pattern would be expected to (1) produce a reduction in errors to locate all four goal locations (i.e., complete a trial), (2) produce a reduction in errors in locating the second and third goal locations because the discovery of each goal location should successively reduce uncertainty about the location of the next goal [see rationale below], (3) produce a decreased tendency to choose a location that is adjacent following discovery of a goal location because such moves do not conform to the pattern, and (4) produce an increased tendency to choose a location that is diagonal following discovery of a goal location because such moves do conform to the pattern.

In addition to errors to complete a trial, we analyzed the number of errors to locate the second goal location following the discovery of the first goal location and the number of errors to locate the third goal location following discovery of the second goal location. A focus on errors at these points in the search transition should not only be sensitive to learning of spatial relations among locations but also be the most sensitive to any differences between the groups because it is at these two points in the search process of locating all four goal locations in which any information provided by the auditory cues should manifest in determining the next goal location. Specifically, the discovery of the first goal location must necessarily be based upon trial-and-error learning; as a result, errors to discover the first goal location would neither provide information about learning of the spatial relations among locations nor reveal any differences between the groups. Similarly, discovery of each goal location should successively reduce uncertainty about the location of the next goal, and perfect learning of the spatial relations among locations would provide unambiguous information about the location of the last goal location for both groups. As a result, discovery of the last goal location would not be sensitive to any differences between the groups.

In contrast, errors to locate the second and third goal locations should be sensitive to both learning of the spatial relations among locations and reveal differences between the groups. With respect to revealing learning of the spatial relations among locations, errors to locate the third goal location should be fewer than those to locate the second goal location because uncertainty for the location of the second goal location given the first should be greater than that of the uncertainty for the location of the third goal location given the first and second. With respect to revealing group differences, in addition to providing information that a goal location had been found, the auditory cues for the Consistent group could also provide participants with their location within the pattern. As a result, errors made in the process of locating the second and the third goal locations could be reduced with the directional knowledge provided by consistent auditory cues. In contrast, this directional knowledge would remain ambiguous for participants in the Inconsistent group. In short, perfect learning of the spatial pattern for participants in both groups should still result in superior performance for participants in the Consistent group (should they learn about their location within the pattern) because the consistent auditory cues remove uncertainty regarding the location of the second and third goal locations that would persist for participants in the Inconsistent group.

1. Method

1.1. Participants

Sixty-four undergraduate students (32 males and 32 females) served as participants. Participants received extra class credit or participated as part of a course requirement.

1.2. Apparatus

An interactive 3-D virtual environment was constructed and rendered using Valve Hammer Editor and run on the Half-Life Team Fortress Classic platform. A personal computer, 19-in. flat-screen liquid crystal display (LCD) monitor, optical mouse, keyboard, and headphones served as the interface with the virtual environment. The monitor (1152 x 864 pixels) provided a first-person perspective of the virtual environment (see top panel, Fig. 1). The arrow keys of the keyboard, the mouse, and the left mouse button allowed the participants to navigate within the environment. Headphones emitted auditory feedback. Experimental events were controlled and recorded using Half-Life Dedicated Server on an identical personal computer.

1.3. Stimuli

Dimensions are length × width × height and measured in virtual units (vu). The virtual environment (1050 × 580 × 416 vu) contained 25 raised bins (86 × 86 × 38 vu) arranged in a 5 × 5 matrix (see bottom panel, Fig. 1). The room was illuminated by a light source centered 64 vu below the ceiling. To provide an orienting cue, the wall opposite the start location (labeled S in Fig. 1) was lighter than the other three.
1.4. Procedure

Participants were randomly assigned to one of two groups: Consistent or Inconsistent. Each group consisted of a total of 32 participants (16 males and 16 females). Participants completed 30 trials in which they searched for four goal locations located among the twenty-five bins. These goal locations were arranged in a diamond pattern. This diamond pattern moved about the search space to a random position from trial-to-trial, but the goal locations always maintained the same spatial relations to each other (i.e., in the shape of a diamond). Participants were required to search for these four goal locations. Participants began each trial at the same starting position (marked “S” in top panel, Fig. 1).

Participants were asked to locate the bins that transported them to the next virtual room. Participants moved via keyboard keys: ↑ (forward), ↓ (backward), ← (left), and → (right). Diagonal movement occurred if two appropriate keys were depressed simultaneously (e.g., left and backward). Movement of the mouse changed the view in a 360° sphere within the virtual environment. Auditory feedback indicated movement within the environment (footstep sounds). Participants selected a bin by jumping into it.

Fig. 1. Top panel: screen-shot from the first-person perspective of the virtual environment search space taken at the start location (S). Bottom panel: overhead screen-shot of the virtual environment search space from three possible trials for the Consistent group (top row) and Inconsistent group (bottom row). For illustrative purposes, the numbers mark the goal locations and the locations of the auditory cues from trial-to-trial (see text for details). Also for illustrative purposes, S marks the position where participants entered the open field and thus started their search for all trials. The position of the diamond pattern was quasi-randomized across trials (see text for details).
To jump into a bin, participants simultaneously moved forward (1) and jumped (left mouse button). Auditory feedback indicated a jump occurred (“huh” sound). For those in the Consistent group, selection of a goal bin resulted in one of four distinct auditory cues: (1) running sound from the Flintstones, (2) 1-up sound from Super Mario Bros., (3) transport sound from Super Mario Bros., and (4) Oompa Loompa whistle sound from Charlie and the Chocolate Factory. All auditory cues were approximately 1-s in duration. These sounds were arranged such that each location within the pattern always specified a unique and consistent auditory cue throughout the experimental session (see Fig. 1 for which auditory cue mapped onto which location within the pattern). Selection of a non-goal bin resulted in different auditory feedback (game over sound from Super Mario Bros.) and required participants to jump out of the current bin and continue searching. For those in the Inconsistent group, the same four distinct auditory cues were provided for the selection of a goal location; however, the locations of these auditory cues within the pattern itself were randomized from trial-to-trial throughout the experimental session (see Fig. 1). For both groups, successful discovery of the first, second, and third goal locations were each followed by auditory feedback, but only successful discovery of all four goal locations resulted in auditory feedback and a 1 s inter-trial interval in which the monitor went black and participants progressed to the next trial.

2. Results

Two separate analyses were used collectively as converging evidence to determine the extent to which participants learned the spatial relations among locations: (1) errors (both to complete a trial and to locate the second and third goal locations), and (2) choice type (i.e., direction of choice following the successful discovery of a goal location). As previously mentioned, errors to locate the second and third goal locations, proportion of adjacent moves (moves not conforming to the pattern) following discovery of a goal location, and proportion of diagonal moves (moves conforming to the pattern) following discovery of a goal location should best serve to isolate spatial pattern learning and illuminate any differences that may exist between the Consistent and Inconsistent groups. As a reminder, a focus on errors in locating the second and third goal locations should not only be sensitive to learning of spatial relations among locations but also be the most sensitive to any differences between the groups because it is at these two points in the search process of locating all four goal locations in which any information provided by the auditory cues should manifest in determining the next goal location.

2.1. Errors to complete a trial

Search behavior was influenced by the spatial configuration of the goal locations as mean errors to complete a trial decreased across trial blocks. Fig. 2 (top panel) shows the mean number errors to locate all four goal locations (i.e., complete a trial) plotted across trial blocks for both groups. As shown, errors to complete a trial decreased across trial blocks for both groups, but the performance of the Consistent group (M = 12.78, SEM = 0.70) was not different from the performance of the Inconsistent group (M = 12.67, SEM = 0.52). These results were confirmed with a two-way mixed analysis of variance (ANOVA) on mean errors to complete a trial with Group (Consistent, Inconsistent) and Block (1–6) as factors which revealed a main effect of Block, F(5, 310) = 19.93, p < .001. There was no effect of Group, F(1, 62) = 0.02, p = .9, and no significant Group × Block interaction, F(5, 310) = 0.32, p = .89.

2.2. Search transition

Fig. 2 (bottom panel) shows the mean errors to locate the second goal location following discovery of the first goal location (i.e., first to second) and the mean errors to locate the third goal location following discovery of the second goal location (i.e., second to third) for both groups. As shown, errors to locate the second and third goal location decreased across trial blocks for both groups. In addition, errors to locate the third goal location were fewer than those to locate the second goal location. However, the performance of the Consistent group (M = 3.62, SEM = 0.34; M = 2.23, SEM = 0.23) was not different from that of the Inconsistent group (M = 3.16, SEM = 0.21; M = 1.91, SEM = 0.13) for either locating the second or the third goal locations, respectively. These results were confirmed with a three-way mixed ANOVA on mean errors to discover a goal location with Group (Consistent, Inconsistent), Goal (Second, Third), and Block (1–6) as factors which revealed main effects of Goal, F(1, 62) = 40.27, p < .001, and Block, F(5, 310) = 11.51, p < .001. The Goal × Block interaction was also significant, F(5, 310) = 3.38, p < .01. No other main effects or interactions were significant, Fs < 2.2, ps > .14. The interaction appears to have resulted from a similar number of errors when locating the second and third goal during Block 3 (p = .19), whereas the number
of errors to locate the second and third goal was different for all other blocks (ps < 0.001).

2.3. Choice type

Fig. 3 (top panel) shows the mean proportion of adjacent moves (i.e., moves that do not conform to the spatial pattern) following discovery of a goal location. As shown, the proportion of adjacent moves following discovery of a goal location decreased across trial blocks for both groups, but the performance of the Consistent group (M = 0.64, SEM = 0.06) was not different from the performance of the Inconsistent group (M = 0.75, SEM = 0.05). These results were confirmed by a two-way mixed ANOVA on proportion of adjacent moves following discovery of a goal location with Group (Consistent, Inconsistent) and Block (1–6) as factors which revealed a main effect of Block, F(5, 310) = 7.93, p < .001. There was no effect of Group, F(1, 62) = 1.98, p = .17, and no significant Group × Block interaction, F(5, 310) = 0.08, p = .99.

Fig. 3 (bottom panel) shows the mean proportion of diagonal moves (i.e., moves that conform to the spatial pattern) following discovery of a goal location plotted across trial blocks for both groups. As shown, proportion of diagonal moves following discovery of a goal location increased across trial blocks for both groups, but the performance of the Consistent group (M = 0.23, SEM = 0.05) was not different from that of the Inconsistent group (M = 0.17, SEM = 0.05). These results were confirmed with a two-way mixed ANOVA on proportion of diagonal moves following discovery of a goal location with Group (Consistent, Inconsistent) and Block (1–6) as factors which revealed a main effect Block, F(5, 310) = 18.82, p < .001. There was no effect of Group, F(1, 62) = 0.94, p = .34, and no significant Group × Block interaction, F(5, 310) = 0.22, p = .95.

3. Discussion

In the present open-field search task, all measures of search performance indicated that participants in both groups learned the spatial configuration of goal locations. Specifically, mean errors to complete a trial and mean errors to locate the second and third goal locations decreased across trial blocks for both groups. In addition, mean errors to locate the third goal location were fewer than those to locate the second goal location. Moreover, choices that did not conform to the diamond pattern (i.e., adjacent choices) decreased across trial blocks whereas choices that conformed the diamond pattern (i.e., diagonal choices) increased across trial blocks. However, participants exposed to consistent auditory cues performed equally well to those exposed to inconsistent auditory cues in all of these measures of spatial relational learning. In short, these results provide no evidence that the presence of the consistent auditory feedback facilitated the learning of the spatial relations among goal locations.

Our results are consistent with prior research showing the learning of spatial relations among locations (e.g., Sturz et al., 2009, 2010; for a review, see Brown, 2006a, b), and strengthen the claim that pattern learning is the process responsible for the reduction of errors across trial blocks by providing multiple analyses that isolate spatial pattern learning (e.g., errors to locate the second and third goal locations, adjacent and diagonal choices following discovery of a goal location). Current results also extend these findings by examining the influence of auditory cues on the learning of spatial relations among locations and suggest that consistent auditory cues do not facilitate this spatial relational learning. Although the presence of visual cues were shown to facilitate the learning of spatial relations among locations both with a square and diamond configuration (Sturz et al., 2009, 2010), the present results do not provide evidence to suggest that the consistent auditory cues facilitated spatial pattern learning.

Obvious questions emerge as to why visual but not auditory cues appear to facilitate spatial pattern learning and why consistent auditory cues do not appear to facilitate spatial pattern learning relative to inconsistent auditory cues. We acknowledge that these issue remains unclear, but we provide some possibilities to explain our obtained results: (1) difference exist between the fixed nature of visual cues and the transitory nature of auditory cues, (2) participants in the Consistent group did not learn the specific assignment of auditory cues associated with each spatial location within the pattern itself, and (3) auditory cues are not as ecologically relevant for spatial outcomes as visual cues.

With respect to the nature of visual versus auditory cues for spatial localization, facilitation of spatial pattern learning occurred when the visual cues were visually present throughout the duration of each trial (see Sturz et al., 2009, 2010) whereas the auditory cues in the present task were transitory following the discovery of each location. As a result, it remains an open question whether utilizing transient visual cues would produce the facilitation effect observed with fixed visual cues. With respect to absence of learning the specific assignment of auditory cues associated with each spatial location, it remains unclear why participants did not
learn the specific outcomes associated with each spatial location despite learning the spatial relations among locations. From a strict weighting of spatial cues approach (e.g., Cheng et al., 2007; Newcombe and Ratliff, 2007; Ratliff and Newcombe, 2008), the consistent auditory cues should have provided an additional spatial cue to assist in reducing uncertainty about the next goal location. Presumably, one possibility is that the spatial relations among locations (the pattern) overshadowed learning about the consistent assignment of auditory cues. Such a possibility would appear to be difficult to reconcile with a strict weighting of spatial cues account of spatial learning but may align with an ecological relevance approach. For example, if visual spatial cues are more ecologically relevant in spatial tasks compared to auditory spatial cues (see Battaglia et al., 2003), it would not be surprising that the spatial relations among visual locations overshadowed the spatial relations among the auditory cues associated with those visual locations.

Finally, the auditory cues for the consistent group could have served as a discriminative stimulus for the next spatial move. The absence of evidence in the present experiment for participants’ ability to utilize these feedback cues as discriminative stimuli raises the question of whether feedback cues can become discriminative stimuli in foraging-type tasks. If couched within the literature on the differential-outcomes effect (see Trapold, 1970), which has been shown to enhance acquisition and accuracy of discrimination tasks (for a review, see Urcuioli, 2005), we find mixed evidence for differential outcome effects in spatial tasks (see Legge and Specht, 2009). Thus, it also appears to be an open question whether utilizing auditory feedback in foraging-type tasks are more or less relevant than visual spatial cues (c.f., Battaglia et al., 2003).

In conclusion, the equivalence in performance of both groups in the present experiment appears inconsistent with strict models of spatial learning that suggest the certainty and variability of a spatial cue is encoded which may directly affect its weighting relative to other spatial cues and its future reliance by a mobile organism (e.g., Cheng et al., 2007; Newcombe and Ratliff, 2007; Ratliff and Newcombe, 2008). Although the exact reasons for the equivocality of the groups in the present experiment remain unclear, future research may be able to adapt the current task to explore the ecological relevancy of auditory and visual spatial cues for humans to assist in clarifying existing theoretical accounts of spatial learning.

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References

Trapold, M.A., 1970. Are expectancies based upon different positive reinforcing events discriminably different? Learning and Motivation 1, 129–140.