A Comparison of the Serial Order Strategy and the Associative Cue Strategy for Decision Making in Wayfinding Tasks

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Abstract /

It has been proposed that in wayfinding, humans can use multiple strategies to decide which direction to take at intersections. One of them is the serial order strategy, where travelers memorize the order in which those directions should be taken. Another is the associative cue strategy, where travelers memorize associations between conspicuous objects along the way, and the directions to take. We designed tasks in which participants had to base their decisions on the serial order strategy (task S), on the associative cue strategy (task A), or were free to use either of those strategies (task SA). We found that performance errors decreased with practice in all three tasks but were higher in A than in S and SA. We conclude that in our study, the serial order strategy was more efficient than the paired associate strategy. We further conclude that this outcome is likely to depend on task demand, which calls for additional research that varies not only the available strategies, but also the task demand.

Keywords /

wayfinding; navigation; route knowledge; spatial cognition; spatial learning

INTRODUCTION

Finding our way through a city or building is a formidable cognitive skill. It includes the integration of spatial information from different sensory modalities, the maintenance of spatial representations in multiple reference frames, decision making, action planning, movement execution and executive control (Wolbers & Hegarty, 2010). These processes can be deployed in a flexible fashion, depending on the environmental layout, the purpose of the way-finding task, available information, prior knowledge and individual preferences (Ekstrom et al., 2018; Hölscher et al., 2009; Wiener et al., 2009).

The present work deals with one specific component of wayfinding, namely, with decision-making at intersections. It has been proposed in the past that humans can use a range of strategies to determine which way to proceed at intersections. With the *serial order strategy*, they recall a series of directions to take (Tlauka and Wilson, 1994; Iglói et al., 2009), such as "turn right at the first intersection, then left at the next." With the *associative cue strategy*, they recall the directions associated with distinctive objects along the way (Tlauka & Wilson, 1994; Waller & Lippa, 2007), such as "turn right at the gas station, then left at the cathedral"; this strategy is a form of paired associate learning (Arndt, 2012). With the *beacon strategy*, they chose directions which incrementally reduce their distance to a widely visible distinctive object (Waller and Lippa, 2007), such as "walk towards the TV tower, the destination is next to it." With the *relative location strategy*, they incrementally reduce their distance to a point defined by several widely visible objects (Morris, 1984; Jacobs et al., 1997), such as "walk towards a point midway between the TV tower and the cathedral." Lastly, with the *cognitive map strategy*, they decide on the direction to take by referring to an internal representation of the environment (Tolman, 1948; O'Keefe and Nadel, 1978), such as "to get from Buckingham Palace to the Cavalry Museum, walk north-east down The Mall, and then turn south into Whitehall." Travelers can switch between strategies on repeated trips (Iaria et al., 2003), and even in the course of a single trip (Hamburger, 2020, Wolbers & Hegarty, 2010). Indeed, the ability to flexibly switch between strategies was found to be a characteristic of good wayfinders (Liben et al., 2010).

To investigate human wayfinding skills, a number of studies asked participants to follow a prescribed route through a virtual maze with four-way intersections. The maze was displayed on a computer monitor in first-person perspective, and participants had to indicate at each intersection which way to proceed. Participants learned the required directions even if all corridors and intersections of the maze looked exactly the same, but they learned them more efficiently if a distinctive visual cue was provided near each intersection (Jansen-Osmann, 2002; Jansen-Osmann & Fuchs, 2006; Waller & Lippa, 2007). These findings suggest that directions can be learned by the serial order strategy, but they are learned more efficiently when both the serial order strategy and the associative cue strategy is available.

In contrast to the above work, other studies found that learning of a prescribed route does not benefit from visual cues near intersections (Lingwood et al., 2015; Tlauka and Wilson, 1994). One possible interpretation for this discrepancy is that visual cues are only beneficial if the 'task demand' is sufficiently high (Hamburger, 2020). This is a conceivable hypothesis if the concept of 'task demand' is not strictly limited to the number of intersections along the route, since available studies reveal no relationship between the number of intersections and the effectiveness of visual cues, as performance improved in the presence of visual cues in studies where the route had eight, nine or twenty intersections (Jansen-Osmann, 2002; Jansen-Osmann & Fuchs, 2006; Waller & Lippa, 2007), but not in studies where the route had six or fifteen intersections (Lingwood et al., 2015; Tlauka and Wilson, 1994). The above discrepancy might therefore be related not only to the number of intersections, but also to other aspects of task demand, such as the cognitive load imposed by concurrent distracting activities (Tlauka & Wilson, 1994), or the familiarity and discriminability of the visual cues.

The above research compared decision making at intersections when only the serial order strategy could be used, or when both the serial order strategy and the associative cue strategy could be used. Decision making has not yet been investigated when only the associative cue strategy could be used. To explore the latter, it would be necessary to disambiguate associative cues from serial order by presenting the same cue-direction associations in a different order on successive trials. On the first trial, for example, participants may encounter a gas station at the first intersection and have to turn left, and they may encounter a school building on the second intersection and have to turn right. On the second trial, they may encounter the school building rather than the gas station at the first intersection and therefore have to turn right rather than left, and they may encounter the gas station at the fifth intersection and therefore have to turn left there. Thus, the direction to proceed would depend only on the identity of the visual cue, not on the serial position of that cue. Such a dissociation between cue identity and cue serial order does not exist in everyday life, but it is a necessary experimental manipulation for evaluating the associative cue strategy separately from the serial order strategy.

In two earlier studies, participants learned a prescribed route while both the serial order strategy and the associative cue strategy was available, and they subsequently were asked to recall the direction associated with each visual cue. Participants recalled the directions with comparable accuracy when the visual cues were presented in the previously encountered order, and when they were presented in a reshuffled order (Hamburger & Röser, 2014; Karimpur et al., 2016). This indicates that participants had learned the cue-direction associations; however, it leaves open whether they learned them incidentally (Brügger et al., 2019; Münzer et al., 2006), or rather used them to decide which direction to proceed across intersections. It also leaves open whether the associative cue strategy is more or less efficient than the serial order strategy. The present study was designed as a first step towards closing this gap in our knowledge. We describe a method for the study of decision making by either strategy, either alone or in combination, and we present a first set of results that compare the performance of the strategies, either alone or in combination.

Human wayfinding skills have been previously investigated in actual buildings and cities, as well as in virtual environments through which participants proceed by walking on a treadmill, by stepping in place, or by operating keys or joysticks. The disadvantage of virtual environments are their lower fidelity: fields of view are smaller, screen resolution limited, and vestibular, proprioceptive and outflow signals about one's movement are degraded or missing. The advantage of virtual environments is their better control of confounding variables such as light and sounds, pedestrian and vehicular traffic, weather conditions, and other subtle details that might serve as orientation cues. The confounders can be placed under the experimenter's full control and precisely replicated across trials and participants (Coutrot et al., 2019; Ruddle et al., 1997).

Human spatial orientation and wayfinding has been found to be more accurate in real-world rather than in virtual environments (Grant & Magee, 1998; Richardson et al., 1999; Waller et al., 1998), although the differences were reduced with increasing difficulty of the wayfinding task (Coutrot et al., 2019), and were eliminated after prolonged exposure to the virtual environment (Waller et al., 1998).

An intriguingly simple virtual environment has been implemented by Cohen and Schuepfer (1980). Participants saw a series of slides, each showing an intersection, and had to indicate for each slide in which direction the route continued. If their response was correct, the next slide was shown, otherwise they had to try again. The authors' main findings were later replicated by a study where seated participants were passively transported through a virtual environment from one intersection to the next (Jansen-Osmann & Wiedenbauer, 2004). The similarity of findings suggests that the optic flow generated by passive transport through the environment may not play a major role for route learning. This might seem surprising at a first glance, given that optic flow is a powerful cue for the monitoring of one's own movement (Wolbers et al., 2007); however, such monitoring may not be essential if the task is to choose the correct direction at intersections. Since this research is about the choice of directions at intersections, it was decided to adopt the Cohen and Schuepfer (1980) paradigm. To enhance task realism, still slides were not presented but instead a simulation of the optic flow that would occur during the approach to an intersection was used.

METHODS

Participants

To determine the number of participants needed, we registered data from six persons per group, and used their scores to calculate Cohen's f for the effect of primary interest, which is the effect of the factor task on the number of errors in the learning phase in a 3(tasks) x 2(trials) analysis of variance. We thus yielded $f = 0.5324$. Entering $\alpha = 0.05$, $1\text{-}\beta = 0.81$, correlation among repetitions = 0.5 and $f = 0.5324$ into G*Power (Faul et al., 2007) yielded a total sample size of 30. We therefore decided to test a total of 36 participants.

Participants were recruited by word of mouth and by written postings. We did not pre-select them with regard to gender, age, profession or social status. They were 35 to 49 years old (mean ±SD: 40.25 ±3.95), and 21 were female. Thirty-three held a university degree, and the remaining three a secondary school degree. All were healthy by self-report, and exhibited no overt sensorimotor or cognitive deficits. All participants signed an Informed Consent Statement before testing began. The research protocol was pre-approved by the Commission for Bioethics of the Institute of Neurobiology of the Bulgarian Academy of Sciences (1–41, 12. July 2019), and was performed in accordance with the ethical standards as laid down in the Declaration of Helsinki.

Participants were evaluated during a single visit to our laboratory, which took about 30 minutes. They engaged first in a learning phase that consisted of three trials, and directly thereafter in a test phase that consisted of three different tests.

Learning Phase - Materials

Participants were seated in front of a 15.6-inch computer monitor, at a viewing distance of about 50 cm. If they wore eyeglasses in everyday life, they continued to wear them during testing. The monitor displayed the color image of a four-way intersection, which participants viewed in first person perspective (Fig. 1). The intersection was created with Unreal Engine® 4.16.2 (Epic Games), a software for the design of virtual environments.

Each experimental trial consisted of a sequence of nine intersections, all looking exactly the same except for a photograph that served as a visual cue. Thus, walls, floors, and ceilings always had the same structure, size, shape, color, and brightness, the photograph always hung from the ceiling at the same location, and it always had the same size and shape. However, a different photograph was displayed at each of the nine intersections. All photographs showed a distinctive building and were photo-edited for mirror symmetry (left portion of Fig. 1), to ensure that they served as visual cues because of their characteristic architectural features, and not because of their asymmetry. This was to avoid, for example, that a turret on the left but not right side of a building signaled participants to turn left. The displayed buildings types ranged from modern to medieval, were prototypical rather than unique, and none of them could be considered as "famous." As such, semantic influence (Hamburger & Röser, 2014) should not influence the study results.

The nine intersections of a trial were presented as PowerPoint® slides. We used the 'animation' function of PowerPoint® to simulate optic flow during the approach to an intersection: after its appearance, each intersection expanded radially by 50% within one second. Once a decision was made to turn left or right at a given intersection (see below), the next intersection appeared and expanded, etc. Thus, we simulated optic flow during the approach to the intersections, but not during the exit from the intersections.

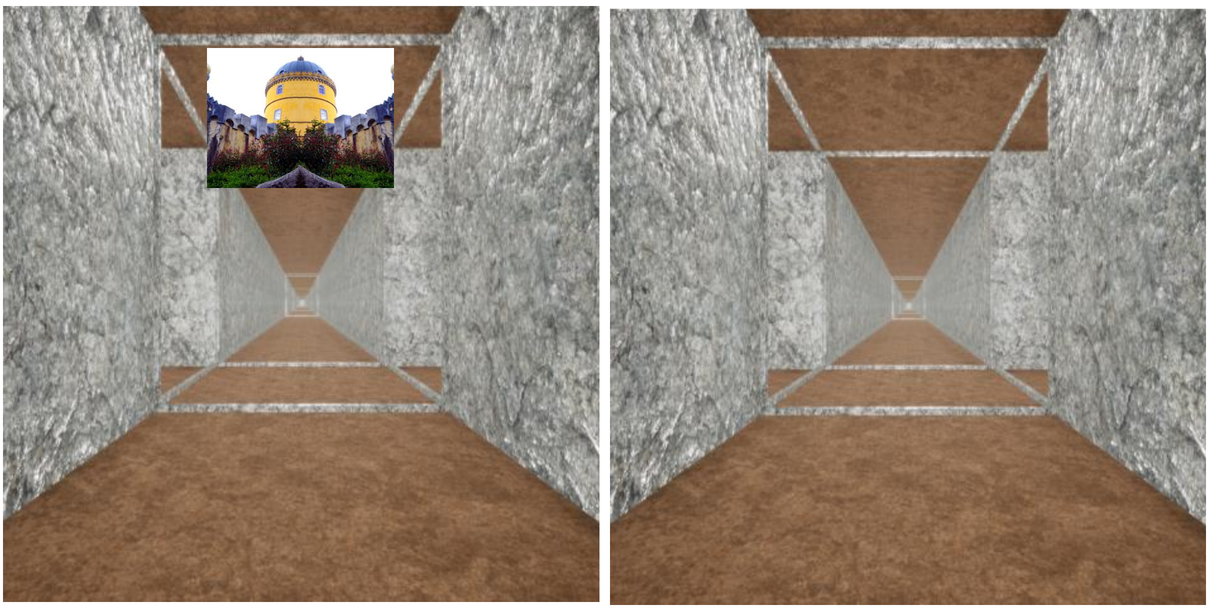

Figure 1 /

Example of an Intersection in the Learning Phase (Left) and in the Serial Order Test (Right)

Note / Participants saw the intersection in first person perspective, as shown. All nine intersections looked the same except for the visual cues, which showed a different distinctive building at each intersection. Visual cues were displayed during the learning phase (left), but not during the serial order test (right).

the approach to the intersections, but not during the exit from the intersections.

Learning Phase - Procedures

The first trial of the learning phase was experimenter-guided. At each intersection, the experimenter said "here you must turn left" or "here you must turn right", and then presented the next slide. The second and third trials of the learning phase were self-guided. At each intersection, participants decided on their own which way to turn by saying "leftwards" or "rightwards." If the decision was correct, the experimenter said "o.k." or "correct." If the decision was wrong, the experimenter said "no, the correct direction is rightwards" or "no, the correct direction is leftwards." In either case, the experimenter then triggered the presentation of the next slide.

Each trial was concluded by a virtual reward: after the ninth intersection participants were shown yet another intersection which displayed a golden trophy in place of a visual cue. They were then told the next trial would now begin or, after the third trial, that the test phase would now begin.

The exact instructions given at the onset of the learning phase were "I will walk with you through a maze with four-way intersections. At each intersection, you will have to turn left or right. In a first walk, I will tell you at each intersection which way to turn. In a second and third walk, you will tell me which way to turn, and I will correct you if necessary." This was followed by a last sentence, which differed between tasks (see below). Note that we instructed participants to "walk" even though they did not actually walk as they were seated. We did so to enhance task realism by facilitating the participants' mental imagery of walking through a maze. Throughout this article we use the term "walk" when directly describing our instructions, but we use the term "trial" otherwise.

Learning Phase - Tasks

Participants were assigned alternately to three tasks. In task SA (Serial order strategy and Associative cue strategy), visual cues were presented in the same order on each trial and each visual cue was associated with the same direction in all trials. For example, the tower depicted in Fig. 1 was displayed at the fifth intersection on all trials, and participants had to turn right at that intersection on all trials. To respond correctly, therefore, participants could use the serial order strategy ("turn right at the fifth intersection"), and/or they could use the associative cue strategy ("turn right at the yellow tower"). The last sentence of instructions for this task was "You will see the photo of a different building at each intersection, which will help you to find the way". The serial order of required directions for task SA is illustrated in Fig. 2.

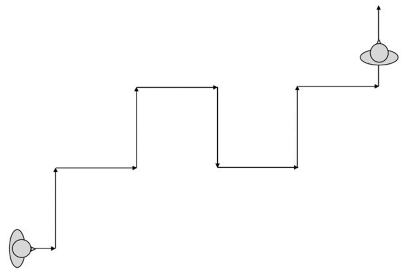

Figure 2 /

Serial Order of Required Directions for Task SA, Task S, and Trial 1 of Task A.

Note / Human body schemes illustrate the participants' orientation before entering the first intersection (bottom left), and after leaving the ninth intersection (top right). Note that participants were not shown this figure, and that they did not physically walk along the displayed route; rather they were seated, saw a sequence of intersections, and only imagined walking across intersections.

In task S (Serial order strategy), visual cues were presented in a different order on each trial but the order of required directions remained fixed across trials. For example, the tower in Fig. 1 was displayed at the fifth intersection on trial 1, and participants had to turn right; another visual cue was displayed at the fifth intersection of trial 2, and yet another at the fifth intersection of trial 3, but participants still had to turn right at the fifth intersection. To respond correctly, therefore, participants had to use the serial order strategy ("turn right at the fifth intersection"). Visual cues were non-informative, and were only displayed to keep visual stimulation comparable across tasks. The serial order of required directions for task S was the same as for task SA. The last sentence of instructions for task S was "You will see the photo of a different building at each intersection, but the photos will not help you to find the way."

In task A (Associative cue strategy), visual cues were presented in a different order on each trial but the association of visual cues with required directions remained fixed across trials. For example, the tower in Fig. 1 was displayed at the fifth intersection on trial 1, at the seventh intersection on trial 2, and at the second intersection on trial 3, and participants had to turn right at the tower irrespective of its serial order. To respond correctly, therefore, participants had to use the associative cue strategy ("turn right at the yellow tower"). The last sentence of instructions for this task was "You will see the photo of a different building at each intersection, and these photos determine which way to turn; if the same photo is encountered on one walk earlier or later than on another walk, it still requires the same turn as before."

Performance in the learning phase was quantified as the number of errors committed on each trial, which is identical to the number of experimenter-provided corrections on each trial. Random performance on the nine two-choice intersections would therefore yield an error score of 4.5.

Test Phase

The *serial order test* was similar to a learning phase trial, except that visual cues were absent, as shown on the right part of Fig. 1. Thus, to respond correctly, participants had to rely on serial order knowledge. Instructions were "In the next test, you walk through the maze once again, but there will be no photos. At each intersection, tell me again which way to turn." No feedback about response correctness was provided. Performance was quantified as the number of errors committed. It was quantified following task SA and task S, but not following task A, since the order of turns varied from trial to trial in the latter task.

In the *cue association test*, all nine visual cues were presented concurrently on the screen. Participants were instructed "In the next test, I will show you a slide with buildings. I will point at each building, tell me the direction related to it, left or right." The experimenter then pointed at each visual cue, in an order that differed from the order(s) in the learning phase. No feedback about response correctness was provided. Performance was quantified as the number of errors committed. It was quantified following task SA and task A, but not following task S, since the cue-direction association varied from trial to trial in the latter task.

In the *direction test*, participants were shown a schematic top view of a human body (shoulders, head, and nose), facing a trophy like the one displayed after the ninth intersection. They were instructed "I will now test your sense of direction. Assume this [experimenter points at the body scheme] is you at the end of the walk. You stand there and look at the trophy. In which direction is the start of the maze? Draw an arrow in that direction." No feedback about response correctness was provided. Performance was quantified as response angle, with 0° representing an arrow that points exactly to the left, and -90° representing an arrow that points exactly forwards. In this reference frame, the true direction to the start of the maze was +31° (broken line in Fig. 4). This test assessed participants' survey knowledge, that is, their knowledge about the spatial layout of the imagined route across nine intersections. We implemented this particular test rather than the judgment of relative directions test (JRD test: Rieser, 1989) since it is more sensitive to small gains in spatial knowledge during route learning (Zhang et al., 2014), and we indeed expected only small gains in our participants' knowledge about the spatial layout of their route. Performance was quantified following task SA and task S, but not following task A, since the spatial layout of the imagined route varied from trial to trial in the latter task.

Data Analysis

Error scores from the learning phase were submitted to an analysis of variance (ANOVA) with the between-factor Task (SA, S, A), and with repeated measures on the factor Trial (2, 3). Levene's tests confirmed that the ANOVA met the prerequisite of homoscedasticity ($p > 0.05$). We checked for an influence of the participants' gender by adding the factor "Gender" to the ANOVA. However, the main effect of Gender and its interaction(s) were non-significant, and the other effects remained virtually unchanged. We therefore report only the outcome without the factor "Gender".

Error scores from the serial order test and from the cue association test were tested against chance (i.e., 4.5 errors) by t-tests of one mean. Response angles from the direction test were analyzed with the circular statistics package CircStats of the software R. The mean angle of responses was calculated with the function circ.mean, and the dispersion of angles with the function circ.disp (dispersion R is a measure of variability for circular data, where R = 0 indicates that angles are uniformly distributed within the full 360° range, and R = 1 indicates that all angles are identical). The distribution of response angles was tested against uniformity with the function rao.spacing (i.e. Rao's Spacing Test, Rao, 1976), and confidence intervals were calculated with the function vm.bootstrap.ci.

RESULTS

Task * Trial ANOVA of the learning phase yielded significance for Task ($F(2,33) = 5.72$; $p = 0.007$; $\eta^2 = 0.26$) and Trial ($F(1,33) = 12.6846$; $p = 0.002$; $\eta^2 = 0.26$), but not for the interaction term ($F(2,33) = 0.35$; $p = 0.710$; $\eta^2 = 0.02$). Post-hoc decomposition by Tukey's HSD tests revealed no significant difference between tasks SA and S ($p = 0.989$), but significant differences emerged between SA and A ($p = 0.020$), as well as between S and A ($p = 0.014$). As Fig. 3 shows, wayfinding errors were smaller in SA and S compared to A, and they were smaller on trial 3 compared to trial 2. Although performance of task A on trial 3 was quite poor, it was better than chance (t-test against a fixed value of 4.5 errors: $t(11) = 3.39$; $p = 0.007$; Cohen's $d = 0.70$).

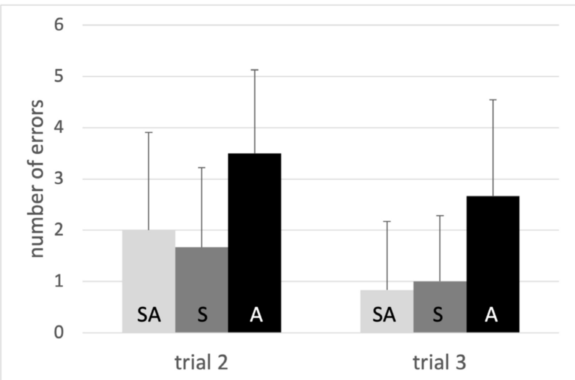

Figure 3 /

Number of Wayfinding Errors on the two Self-Guided Trials of the Learning Phase

Note / Bars show across participant means and whiskers show between-participant standard deviations. The three tasks are coded by different bar shadings.

The mean standard deviation of error scores in the serial order test was 1.75 ±2.01 following task SA, and 0.92 ±1.51 following task S. The corresponding outcome in the cue association test was 2.33 ±1.56 following task SA, and 2.50 ±2.15 following task A. All four outcomes were significantly lower than the chance score of 4.5 ($t(11) = 4.75$; $p < 0.001$, $t(11) = 8.25$; $p < 0.001$, $t(11) = 4.82$; $p < 0.001$, and $t(11) = 3.22$; $p = 0.008$, respectively).

The outcome of the direction test is illustrated in Fig. 4. Response angles were scattered throughout much of the full 360° range, with more responses in the left rather than the right hemispace. Accordingly, Rao's test yielded a significant deviation from a uniform distribution ($U(N = 24) = 162.82$; $p < 0.05$). The mean angle was +13.19° (cf. solid arrow in Fig. 4), and the angular dispersion was R = 0.54. The 95% confidence interval for the mean ranged from -14.15° to +43.66°; it therefore included both the true direction towards the start of the imagined maze (+31°) and the direction due left (0°). The difference between responses following task SA and those following task S was not significant ($t(22) = 0.41$; $p = 0.688$).

DISCUSSION

Several previous studies evaluated decision making in wayfinding tasks where only the serial order strategy can be used, or when both the serial order strategy and the associative cue strategy can be used. The present study is the first to also evaluate decision making when only the associative cue strategy can be used. To this end, we modified an available experimental paradigm (Cohen and Schuepfer, 1980; Wiener et al., 2012) which isolates decision-making at intersections from other cognitive processes that normally take place during wayfinding (see Introduction).

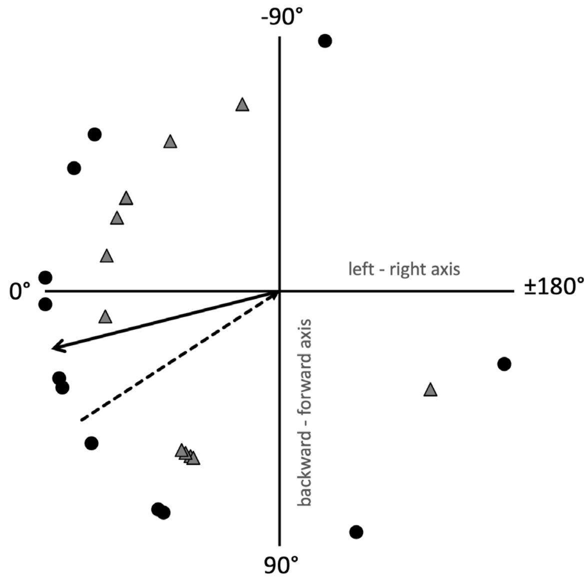

Figure 4

Distribution of Response Angles in the Direction Test

Note / 0° corresponds to responses directed towards the participants' left shoulder, -90° to responses directed towards the participants' nose, etc. The broken line indicates the correct direction towards the start of the imagined maze, and the solid arrow indicates participants' mean response direction, 13.19°. Each symbol represents the response of one person. For clarity, responses following task SA are plotted along a larger perimeter (black circles) than those following task S (grey triangles).

It was found that the number of errors decreased significantly from trial 2 to trial 3 of the learning phase, and that it was comparable in task SA and in task S. Thus, performance was not appreciably better when both the serial order strategy and the associative cue strategy were available, compared to when only the serial order strategy was available. This outcome is in accordance with some (Lingwood et al., 2015; Tlauka & Wilson, 1994), but not with other earlier studies (Jansen-Osmann, 2002; Jansen-Osmann & Fuchs, 2006; Waller & Lippa, 2007). As pointed out in the Introduction section, the discrepancy between studies might well be related to different task demands (Hamburger, 2020), in that availability of the associative cue strategy only becomes beneficial for performance if the task is demanding enough.

Further, it was found that the number of errors was significantly higher in task A than in task SA and in task S. Thus, performance was poorer when only the associative cue strategy was available, compared to when only the serial order strategy was available or when both strategies were available. Again, this apparent disadvantage of the associative cue strategy might well depend on task demand; the associative cue strategy might yield better rather than poorer performance than the serial order strategy when the task is demanding enough (Hamburger, 2020).

In task A, visual cues were presented in a different order on each trial. This was necessary to deconfound route learning by the associative cue strategy from route learning by the serial order strategy, but it deviates from our experience in everyday life, which possibly had a negative impact on the participants' performance on task A. A related argument can be made regarding task S. There, all intersections looked exactly alike, which served to deconfound the serial order strategy from the associative cue strategy, but it again deviates from our experience in everyday life and thus might impact performance on task S. One possible approach for scrutinizing such an impact in future research would be to compare performance on task A to that on a control task where participants also form associations between nine stimulus items and two response items, but those associations have no everyday-life connotation. Similarly, one could compare performance on task S to that on a control task where participants also learn a sequence of nine binary items, but that sequence has no everyday-life connotation.

In sum, the present study introduced a new methodological approach, and presented a first set of data collected with this approach. Like most earlier studies, however, it did not explore the role of task demand. To overcome this limitation, our current research expands the same methodological approach by varying the task demand in multiple ways: we vary the number of intersections, the number of potential directions at each intersection, the presence or absence of concurrent distracting tasks, as well as the familiarity (Hamburger & Röser, 2014), ambiguity (Strickrodt et al., 2015), and salience (Dong et al., 2020) of visual cues.

The spatial knowledge that participants acquired during the learning phase was assessed during the subsequent test phase. Following task SA, performance on the serial order test and on the cue association test was significantly better than chance, which confirms the outcome of earlier work (Cohen & Schuepfer, 1980; Hamburger & Röser, 2014; Jansen-Osmann & Wiedenbauer, 2004; Karimpur et al., 2016; O'Malley et al., 2018; Wang et al., 2014). Following task S, performance on the serial order test was significantly better than chance, and following task A, performance on the cue association test was significantly better than chance. Thus, all participants had acquired substantial spatial knowledge of the types that were available to them.

The direction test was included to find out whether participants acquired the spatial layout of an imagined route in tasks SA and S, i.e., in those tasks where that route would be consistent across trials (Fig. 2). We found that responses angles were not randomly distributed throughout the full 360° range, but rather varied within a wide range; the confidence interval included the true direction towards the start of the maze. It therefore appears that participants had acquired a vague knowledge about the spatial layout of the maze. This is not trivial, since participants did not physically walk along a route, but rather were seated and only *imagined* walking along that route.

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Data Availability Statement: Stimulus materials and raw data are available from the corresponding author on reasonable request

Authors' Contributions: Otmar Bock conceived the experiment, performed statistical analyses, and wrote the first draft of the manu script. Steliana Borisova collected the data, performed preliminary analyses, and critically commented on the manuscript.

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