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Interplay of wayfinding strategies in route repetition and route retracing

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Abstract
This study explores the interplay of navigation strategies in route repetition (repeating a recently travelled route) and route retracing (returning to the start location of a recently travelled route). Specifically, we investigated how sequence knowledge contributes to route repetition and retracing. In the learning phase, participants passively transported along a route. In the test phase, they were then asked to repeat or retrace the route. Decision points were either presented in an order coherent with the learning phase (from start to destination in route repetition, or from destination to start in route retracing), or in a randomised order. As expected, participants performed better in route repetition than in route retracing. Performance declined when intersections were presented in a randomised order indicating that sequence knowledge contributed to route repetition and route retracing. Presenting intersections in an order coherent with learning boosted performance specifically on the first part of the route during route repetition. This effect was not observed during route retracing. These results show that sequence knowledge is utilised differently during route repetition and retracing. We argue that participants use a "sequence of turns" strategy alongside associating landmarks with direction changes during route repetition, and that it is unlikely that route retracing relies on the same type of sequence knowledge. Instead, we believe route retracing utilises knowledge about the sequence in which decision points are encountered. Overall, the findings highlight a complex interplay of different strategies in route repetition and retracing, shedding light on how navigators utilise sequence knowledge for effective navigation.

Keywords
Navigation; wayfinding; route learning

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Introduction

Repeating a previously travelled route (route repetition) or retracing a recently travelled route from the destination back to the start location (route retracing) are everyday navigation tasks that are supported by various navigation mechanisms and strategies (Bock et al., 2024; Tlauka & Wilson, 1994; Waller & Lippa, 2007; Wiener et al., 2012, 2020). Studies aiming to investigate strategies supporting route navigation typically aim to isolate single strategies, for example, by manipulating landmark information (Waller & Lippa, 2007). Consequently, our understanding of how navigation strategies interact during route navigation is limited. We will address this question in the current study.

Route repetition—repeating a previously travelled route—is often thought of as the prototypical egocentric navigation task, in which spatial information is encoded from the navigator's perspective (e.g., Wolbers & Wiener, 2014). Depending on the availability of landmark information at decision points, navigators rely on different route learning strategies. In the absence of any landmark information, routes can be memorised as a sequence of turns along the route ("left–right–left–straight"; Tlauka & Wilson, 1994). This "sequence of turns" strategy is effective for the first few decision points, after which performance declines substantially (Waller & Lippa, 2007). This is not surprising as leaving out a single turn or incorrectly

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adding a turn will render the remaining part of the sequence incorrect leading to wrong turns.

Landmarks at decision points substantially improve route learning and route repetition performance (Heft, 1979; Jansen-Osmann, 2002). Landmarks are used to recognise places or decision points at which articular movement actions are required to follow a route (Siegel & White, 1975; Trullier et al., 1997). The resulting route knowledge is typically described as a series of stimulus–response (S-R) associations, place recognition-triggered responses, or place/landmark-actions associations ("Turn right at gas station"; Waller & Lippa, 2007). Landmarks can also function as beacons in route learning and route repetition if they are positioned such that they can be associated with one of the movement options (beacon strategy: "Turn in direction of gas station"; Waller & Lippa, 2007).

When learning to repeat routes, navigators also learn about the sequence in which places are encountered (Hilton, Johnson, et al., 2021; Hilton, Wiener, et al., 2021). Such sequence of place knowledge is neither sufficient nor necessary for route repetition as it itself does not provide information about the direction in which a route continues. However, it links neighbouring place–action associations (Schinazi & Epstein, 2010), it can be used to distinguish visually similar situations along the route (Strickrodt et al., 2015), and to predict upcoming places/intersections, and therefore providing a building block for more flexible navigation behaviour (Grzeschik et al., 2021; Trullier et al., 1997).

Imagine parking your car in an unfamiliar part of a city, walking to a shop, and then returning to the car. On your way back to the car you are retracing your route. Route retracing, that is, navigating a recently travelled route from the destination back to the start place, despite being a frequent navigation task, has received much less attention in the literature than route repetition. Importantly, route retracing cannot be achieved with the purely egocentric strategies described for route repetition as decision points are approached from a different direction than during learning (Wiener et al., 2012). Understanding the direction in which the retraced route continues therefore requires an understanding of the spatial relationship between the approach direction, the decision point, and the depart direction (Grzeschik et al., 2021; Wiener et al., 2013, 2020). Such an understanding is often referred to as allocentric knowledge or an allocentric representation of the spatial situation (Ekstrom et al., 2014).

It is currently unclear what role sequence knowledge plays in route retracing. The "sequence of turns" strategy described for route repetition above cannot easily be employed during retracing where intersections are encountered in the opposite order and direction changes need to be mirrored. However, in an earlier study we have shown that participants' knowledge about the order in which landmarks are encountered along a route was comparable when repeating and retracing a route (Wiener et al., 2012). It is therefore conceivable that sequence knowledge contributes to route retracing.

The main aim of the current study was to investigate the role of sequence knowledge in route navigation and how it interacts with other route navigation strategies. For route repetition, we were specifically interested in the interplay of the "sequence of turns" strategy and the "associative cue" strategy. To study this interplay, we systematically manipulate the order in which intersections were encountered when assessing route knowledge in the test phase. If intersections were presented successively (i.e., in an order coherent with the learning phase), both strategies could work in parallel. However, if intersections were presented in a randomised order during the test phase, the "sequence of turns" strategy could not be employed and participants had to rely on the associative cue strategy alone. As mentioned above, it is an open question if and how sequence knowledge is utilised in route retracing and we explored this question here.

In the experiment, participants in all conditions were passively transported along a route with 12 intersections. Each intersection featured a unique house which served as a landmark while all other houses along the route were identical. In the test phase, participants were then asked to either repeat the route (from start to destination) or retrace the route (from destination back to the start). Intersections were presented one at a time either successively (coherent with the order during learning) or in a randomised order, resulting in four conditions.

In line with earlier research, we expected route learning and navigation performance to be better in route repetition than in route retracing (Wiener et al., 2012). If sequence knowledge supported route repetition as well as route retracing even in the presence of landmarks, we expected that presenting intersections successively during the test phase (i.e., in an order coherent to that during learning) will result in better performance in both the repetition and retracing tasks than presenting them in randomised order. Finally, Waller and Lippa (2007) suggested that the "sequence of turns" strategy only supports route repetition in the initial part of the route, that is, on the first few intersections. If the "associative cue" and "sequence of turns" strategy interact during route repetition, we expected a performance increase primarily in the initial part of the route when intersections are presented successively (in an order coherent with that during learning).

Method

Participants

A total of 109 participants completed the experiment (63 females, 46 males; M_{age}: 21.18 years, ±3.15 years). Participants were students at Bournemouth University and

Please press SPACE when ready to view the route.

Please press SPACE when ready to continue.

Please use left, right and forwards arrow keys to indicate correct direction at upcoming intersection.

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Figure 1. Screenshots taken during the learning phase (upper row) and during a repetition test phase trial (lower row). (a) The view at the start of the learning phase before passive transportation starts. (b) Screenshot taking at an intersection. (c) View at the end of the learning route. The destination intersection of the route features a telephone box. (d) View at the beginning of a repetition test trial from the start location towards the first intersection. (e) Screenshot taking while navigating towards the next intersection. (f) View at the end of a test trial before participants report their response, that is, the direction in which the route continues.

obtained course credits for participation. Of the 109 participants, 27 (14 females, 13 males) took part in the replicate random condition, 27 (17 females, 10 males) took part in the replicate successive condition, 28 (16 females, 12 males) took part in the retrace random condition, and 27(16 females, 11 males) took part in the retrace successive condition. The conditions are explained in more detail below.

This study was not designed to investigate sex differences and we therefore do not include sex as a factor in the analysis presented below. We have, however, undertaken a preliminary analysis comparing overall performance between male and female participants and have found no differences in performance, $F(1, 107)=0.01$, $p=.94$.

The virtual route

We designed a single route with 12 four-way intersections which featured 4 right turns, 4 left turns, and 4 straights. Each intersection featured a unique house that served as a landmark and that was placed at all four corners of the corresponding intersection (the brown house with the black features in Figure 1b is one of the unique landmarks). All road sections between intersections looked identical, all featuring the same red houses on the right and left sides (see Figure 1e). The only distinguishing features along the route were the start location with the black car (see Figure 1a), the destination with a telephone box (Figure 1c), and the houses/landmarks placed on the corners of the 12 intersections (each intersection featured different houses, e.g., Figure 1b). Placing the same house (i.e., landmark) at each corner of an intersection prevented participants from using beacon-based strategies such as memorising to turn towards or away from a particular landmark or house (Waller & Lippa, 2007; Wiener et al., 2013). Instead, participants had to rely on either the associative cue strategy by associating a direction with a landmark (e.g., "Turn right at Gas station") or the sequence of turns strategy by memorising the sequence of movement direction at the intersections (e.g., left, right, left, straight . . .; Waller & Lippa, 2007). Note, however, that the *sequence of turns strategy* could only be used as the conditions in which the intersections were presented in a successive order, as explained in detail below (see also Figure 2).

The route learning task

We used the *Route Learning and Navigation* Test battery (https://osf.io/mx52y/; Wiener et al., 2020) to set up the experiment. The experiment consisted of six experimental sessions. Each experimental session consisted of a learning phase and a test phase. That is to say, participants were exposed to the same virtual route six times and their route knowledge was assessed after each exposure, which allowed us to assess learning over the course of the experiment.

- *Learning phase*: In the learning phase, participants were passively transported along the virtual route at a speed of 7.6 m/s and participants were instructed to memorise the route. The learning phase was identical for all experimental conditions (detailed below). All participants were transported along the same route in each in each of the six learning phases.

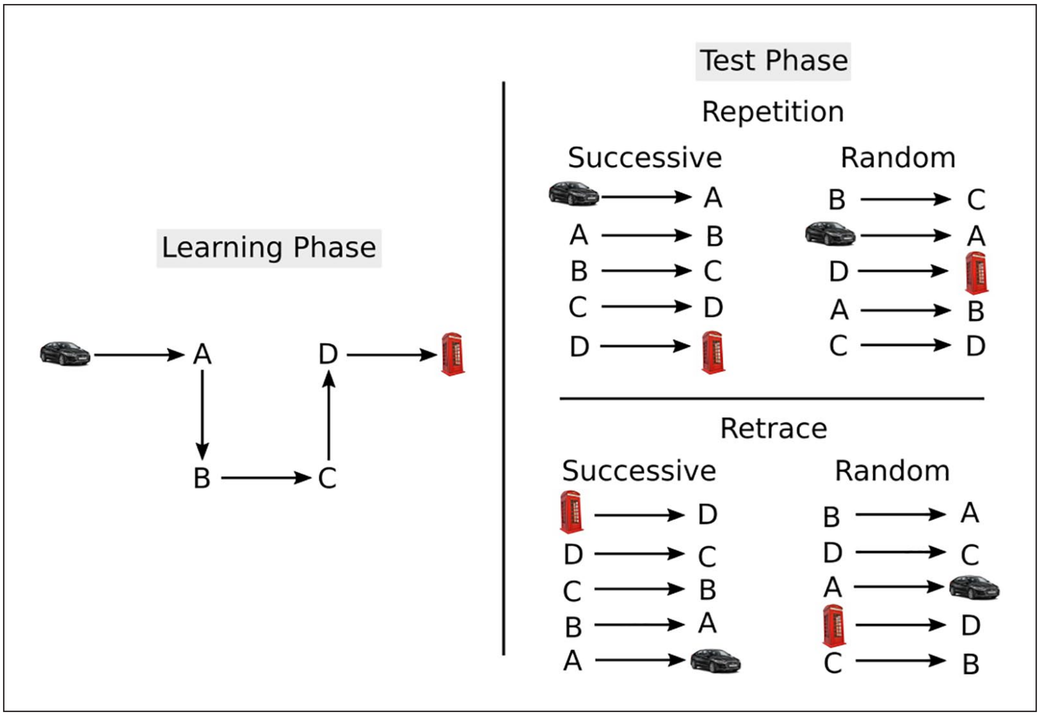

Figure 2. Schematic drawing using a shortened route to illustrate the experimental phases and the four experimental conditions. During the learning phase (left), participants are navigated along the route. The start of the route was marked by the car, the end of the route by the telephone both. The letters represent the different landmarks available at the intersections. In the test phase (right) participants were either asked to repeat the route (top-right) or to retrace the route (bottom-right) and intersections were either presented successively or in a randomised order. Each trial in the test phase started at one intersection and participants were transported to the next intersection and asked to report the direction in which the route continues given the current travel direction (repetition or retrace).

- *Test phase*: In the test phase, participants were passively transported towards each of the 12 intersections along the route and asked to indicate the direction to continue along the route given the current travel direction (see below). Participants responded by pressing the arrow key that corresponded to the travel direction (left, right, straight/up). Responses and response times were recorded. Importantly, a single test phase trial ended as soon as participants indicated the direction in which they thought the route continued. This ensured that participants did not receive feedback in the test phase, therefore clearly separating the learning and test phases. The travel direction in the test phase and the order in which the 12 intersections were presented depended on the exact condition, as explained below.

Experimental conditions

As we were interested in the strategies participants employed in each condition and in order to avoid possible carryover effects, we used a between design. Specifically, we employed a 2 × 2 design with the between factors travel direction (forward [route repetition], backward [route retracing]) and intersection order (successive, random). Participants were pseudo-randomly (controlling for sex ratio between condition) assigned to one of the four conditions (repetition successive, repetition random, retracing successive, retracing random).

Travel direction

Route repetition. Route repetition resembles a classical route learning task in which participants are first shown a route during the learning phase and then have to repeat that route in the same direction, that is, from the start of the route to the destination.

Route retracing. In route retracing, participants are shown the route during the learning phase, but then have to retrace the route from the destination back to the start location (e.g., Wiener et al., 2012).

Intersection order

Successive intersection order. In the test phase, intersections are presented in an order that is coherent with the order during the learning phase. That is to say, during route repetition, the 12 intersections are presented in the order in

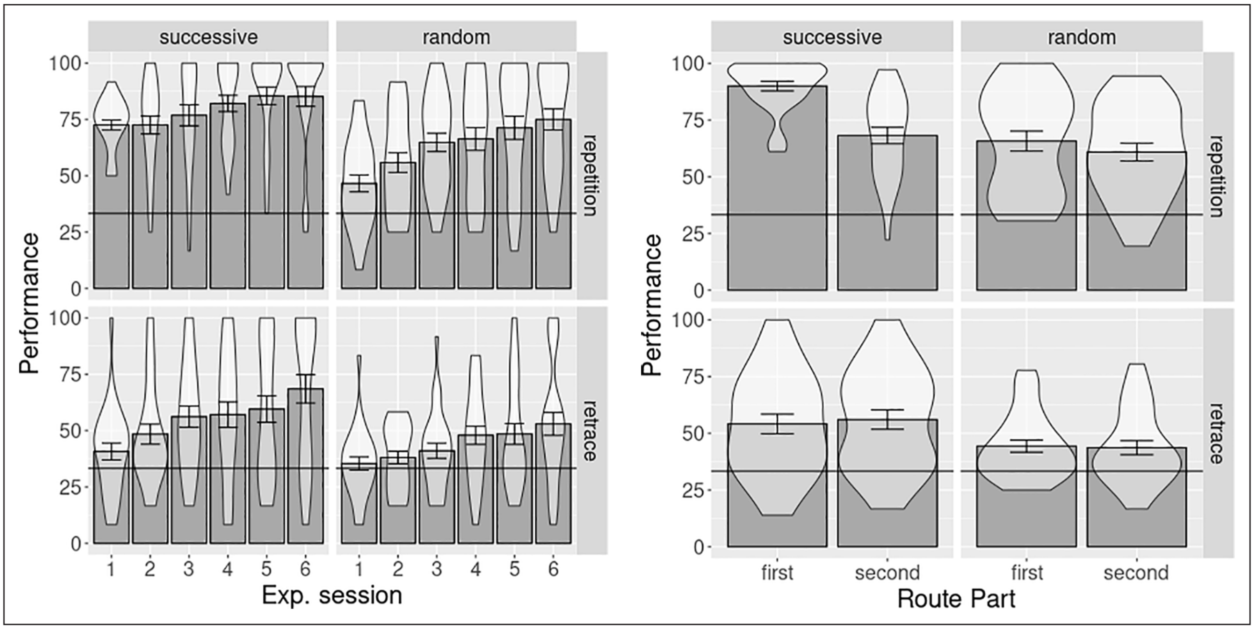

Figure 3. Left: route learning performance (mean accuracy) in the four conditions (replicate successive order, replicate random order, retrace successive order, and retrace random order) as a function of experimental session; right: performance for the four conditions for the first part (Intersections 1–6) and the second part (Intersections 7–12) of the route.
Error bars represent standard error of the mean.

which they were experienced during the learning phase (i.e., 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12). In route retracing, the intersections are presented in the reverse order in which were experienced during the learning phase (12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, 1). The successive intersection order presentation allows participants to use the sequence of turns strategy, the associative cue strategy, or a combination of these strategies to solve the task.

Random intersection order. In the test phase, intersections are presented in a randomised order. Presenting intersections in randomised order in the test phase prevents participants from using the sequence of turns strategy.

Procedure

Participants came to the Psychology Department at Bournemouth University to complete the experiment which took between 45 and 60 min. They were provided with an information sheet outlining the aims and general procedure of the study. After providing informed consent they were pseudo-randomly assigned to one of the four conditions, ensuring an equal gender split between conditions. Participants were carefully instructed about the condition they were in and were given a demonstration of the task and the specific condition they were assigned to using a route with just three intersections. If participants indicated they understood the task and had no further questions, the experiment began. The task was presented on a computer with a large 42-in. screen.

Results

Performance

To analyse participants' navigation performance, we assessed the accuracy of single response in the test phase. Performance represents the mean accuracy or the percentage of correct responses. We ran a 2 × 2 × 2 × 6 ANOVA with the following factors: task (repetition, retrace), test order (successive, random), route part (first [Intersections 1–6], second [Intersections 7–12]), and experimental session (1–6). The ANOVA revealed that participants performed better in the repetition than the retracing task (71.22% vs. 49.44%), main effect of task: $F(1, 105) = 40.96$, $p < .001$, $\eta_p^2 = .281$, that performance was better when intersections were presented in the successive order than during learning as compared with a random order (67.10% vs. 53.49%; main effect of order), $F(1, 105) = 15.74$, $p < .001$, $\eta_p^2 = .130$, that performance increased over the course of the experiment (from 48.70% in Session 1 to 70.26% in Session 6; main effect of experimental session: $F(5, 525) = 26.88$, $p < .001$, $\eta_p^2 = .204$), and that performance was higher in the first than the second part of the route (63.34% vs. 57.10%), main effect of route part, $F(1, 105) = 22.35$, $p < .001$, $\eta_p^2 = .176$, see Figure 3.

Of the two way interactions, task × route part, $F(1, 105) = 27.10$, $p < .001$, $\eta_p^2 = .205$, and order × route part, $F(1, 105) = 7.06$, $p < .01$, $\eta_p^2 = .063$, and experimental session × route part, $F(5, 525) = 3.95$, $p < .01$, $\eta_p^2 = .036$, were significant. Of the three-way interactions only task × order × route part, $F(1, 105) = 13.57$, $p < .001$, $\eta_p^2 = .114$,

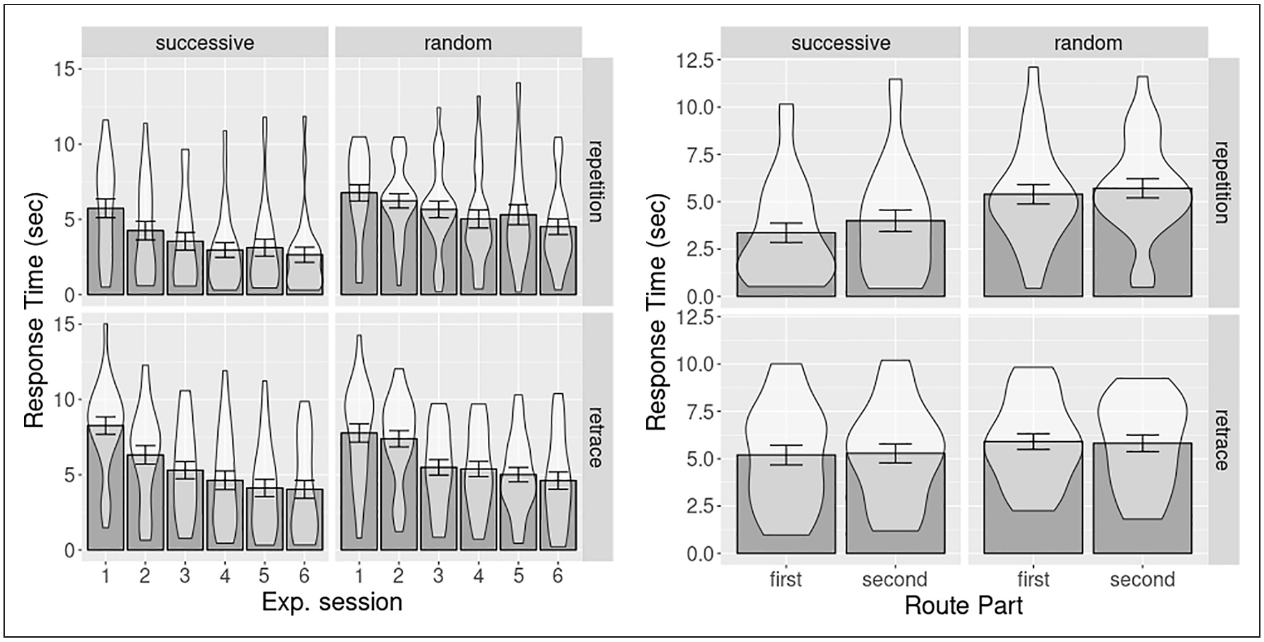

Figure 4. Left: response time for correct trials in the four conditions (replicate successive order, replicate random order, retrace successive order, and retrace random order) as a function of experimental session; response times for correct trials for the four conditions for the first part (Intersections 1–6) and the second part (Intersections 7–12) of the route.
Error bars represent standard error of the mean.

was significant and the four-way interaction was not significant. Figure 3 suggests that these interactions are driven by substantially higher performance in the first part of the route compared with the second part of the route in the repetition condition in which intersections were presented successively. For all other conditions (repetition random, retrace successive, retrace random), performance in the first and second parts of the route was comparable. Post hoc tests confirm that performance differences between the first and second parts were significant only in the successive repetition condition, 90.02% versus 68.21%; Welch's *t*-test: $t(42.15)=5.21$, $p<.001$. None of the other comparisons of performance between the first and second parts of the route for the different conditions were significant (all $p>.05$, see right panel in Figure 3). These results demonstrate that participants benefitted from presenting the intersections in the successive order as during training only on the first part of the route and only when asked to repeat the route, not when asked to retrace the route.

Finally, performance all conditions (replicate successive order, replicate random order, retrace successive order, and retrace random order) for both the first and second parts of the route (see right panel of Figure 3) were significantly above change level (all $p<.01$).

Response times

Only correct trials were included in the response time analysis. The low performance, particularly in early sessions in the retrace condition, led to missing data. As a result we did not include experimental session in this analysis. Instead, we ran a 2 × 2 × 2 ANOVA with the following factors: task (repetition, retrace), test order (successive, random), and route part (first [Intersections 1–6], second [Intersections 7–12]). The ANOVA revealed shorter response times in the repetition than the retracing task, 4.59 versus 5.54 s; main effects of task: $F(1, 105)=4.58$, $p=.03$, $\eta_p^2=.042$, that response time was shorter when intersections were presented in the successive order (i.e., the same order than during learning) compared with a random order, 4.43 versus 5.69 s; main effect of test order: $F(1, 105)=5.03$, $p=.03$, $\eta_p^2=.046$, and that response times were shorter on the first than the second part of the route, 4.97 versus 5.20 s; $F(1, 105)=10.02$, $p<.01$, $\eta_p^2=.087$; see Figure 4.

While none of the interactions reached significance, the task × route part interaction approached significance, $F(1, 105)=3.89$, $p=.051$, $\eta_p^2=.036$. Given that the task × route part interaction was so close to significance, we decided to further explore this effect by comparing response times between route tasks for the first and second parts of the route. These comparisons only rendered one significant result: participants responded faster on the first part of the route in route repetition compared with the first part of the route during route retracing, 4.58 versus 5.11 s; Welch's *t*-test: $t(103.64)=-2.30$, $p=.02$. None of the other comparisons were significant (all $p>.05$).

Figure 4 shows that response times declined over the course of the experiment (in all conditions) from 7.14 s in the first experimental session to 4.00 s in the sixth experimental session (correlation between response time and experimental session: $r = .95$, $p < .01$).

Discussion

The aim of the current study was to investigate how route learning strategies interact during route repetition and route retracing. As predicted, participants performed better when repeating than when retracing a route, and when intersections were presented in the successive order than during training as when they were presented in a randomised order. Importantly, this benefit from presenting the intersection in the successive order during training was particularly pronounced in the first part of the route when repeating routes.

Our results confirm earlier findings that route retracing is more difficult than route repetition (Wiener et al., 2012, 2020). This result is in line with the interpretation that route repetition is supported by simpler mechanisms than route retracing. Specifically, route repetition is typically thought to be supported by egocentric navigation strategies in which spatial information is encoded from the perspective of the navigator, such as the associative cue strategy (e.g., "Turn left at Gas Station"), the beacon strategy ("At intersection turn towards Gas Station"), or the sequence of turn strategy (e.g., "Left–Right–Straight–Left"; Waller & Lippa, 2007). During route retracing, however, intersections are approached from directions different to those during learning. Consequently, navigators need to abstract from viewpoint-dependent or egocentric memories. In our earlier work, we have argued that this can be achieved by perspective-taking or by encoding the spatial relationships between the corridor from which an intersection is approached and the direction in which the route proceeds (Wiener et al., 2012, 2020).

Despite these differences in underlying mechanisms, both route repetition and retracing were affected by our order manipulation. Specifically, performance dropped in both tasks markedly and response times increased when intersections were presented in a random order in the test phase. We argued that disrupting the sequence in which intersections are presented in the test phase should affect any route learning strategy that relies on sequence knowledge, such as the sequence of turn strategy (Bock et al., 2024; Waller & Lippa, 2007). Importantly though, performance remained above chance level even if intersections were presented in randomised order in the test phase. These results demonstrate (1) that local information available at intersections, that is, place identity and movement direction which can give rise to place–direction associations (cf. Bock et al., 2024; Hilton, Johnson, et al., 2021) is sufficient to repeat as well as retrace a route, and (2) that sequence information supports route navigation even in the presence of landmarks at decision points, highlighting an interplay of different route navigation strategies.

How is sequence information used to inform route navigation? Earlier studies investigating route repetition have shown that neighbouring places along a route are associated (Schinazi & Epstein, 2010), and that participants can navigate along routes in which all decision points are visually identical (Bock et al., 2024; Tlauka & Wilson, 1994; Waller & Lippa, 2007). The latter result demonstrates that participants can memorise the sequence of turns along a route to then repeat it. Interestingly, Waller and Lippa (2007) argued that this sequence of turn strategy is effective only in the early part of the route (on the initial 5–6 intersections), after which participants started guessing. This notion is in line with our findings that performance benefits from presenting the intersections in a successive order (i.e., in the same order than in the learning session) were particularly pronounced in the first part of the route (i.e., for Intersections 1–6) when repeating the route. We also reported shorter response times for these first six intersections during route repetition. Together, these results strongly suggest that participants used a "sequence of turns" strategy during route repetition in the first half but not the second half of the route. This highlights that the nature of the interplay between route navigation strategies is complex and cannot be explained by a simple model, which assumes that multiple suitable strategies are employed at the same time. Instead, it seems likely that navigators choose or switch between strategies during navigation depending on the situation, specific wayfinding task and on what strategy yields the best results.

It is less clear how participants benefitted from sequence knowledge in the retrace condition. This is because memorising the sequence of turns during route learning requires substantial reorganisation if using this information during route retracing where intersections are encountered in the opposite order. While we have seen a specific performance benefit from sequence knowledge during route repetition in the first part of the route, no such benefit for either the first or the last part of the route (which is the encountered first during retracing) is evident in route retracing. Instead, presenting the intersection in a successive order (opposite to the order experienced during learning) during route retracing seems to benefit the early and late part of the route equally. We also did not see a difference in response times depending on whether the intersections were presented successively or in a randomised order. These results suggest that it is unlikely that participants used a "sequence of turns" strategy during route retracing. Thus, the process by which sequence knowledge supports route retracing appears to be different from that during route repetition and should be subject to further investigation.

Note that presenting the intersections in a randomised order during the test phase not only disrupts the sequence of turns strategy (Tlauka & Wilson, 1994; Waller & Lippa, 2007), but any strategy that relies on or draws upon knowledge about the order in which intersections were encountered along the route. A series of earlier studies demonstrated that participants in typical route repetition tasks also learn about the sequence in which intersections or places are encountered (Hilton, Johnson, et al., 2021; Hilton, Wiener, et al., 2021) even though this knowledge on its own, that is, without direction information, is not sufficient to support route navigation. Knowledge about the sequence of places/intersections does, however, contribute to navigation. For example, it helps distinguishing visually similar intersections along a route (Strickrodt et al., 2015), and it supports the formation of survey or cognitive map-like knowledge (Hilton & Wiener, 2023). While the specific mechanism by which sequence of intersection knowledge might support route retracing is currently unknown, it is interesting to note that performance in naming the next intersection along the route is comparable in route repetition and route retracing (Wiener et al., 2012), demonstrating that this knowledge is readily accessible in both directions. Further research is needed to investigate the exact role and use of sequence knowledge in route retracing.

In conclusion, the results from this study suggest that (1) route repetition and route retracing are supported by different mechanisms, (2) different types of sequence knowledge supports route repetition (sequence of turns) and route retracing (sequence of places), and (3) the interplay between different route navigation strategies is flexible depending on the specific task and condition.

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