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ORIGINAL ARTICLE

Unitization of route knowledge

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Abstract There are many theories that explain how route knowledge is acquired. We examined here if the sequence of elements that are part of a route can become integrated into a single unit, to the extent that the processing of individual transitions may only be relevant in the context of this entire unit. In Experiments 1 and 2, participants learned a route for ten blocks. Subsequently, at test they were intermittently exposed to the same training route along with a novel route which contained partial overlap with the original training route. Results show that the very same stimulus, appearing in the very same location, requiring the very same response (e.g., left turn), was responded to significantly faster in the context of the original training route than in the novel route. In Experiment 3, we employed a modified paradigm containing landmarks and two matched routes which were both substantially longer and contained a greater degree of overlap than the routes in Experiments 1 and 2. Results were replicated, namely, the same overlapping route segment, common to both routes, was performed significantly slower when appearing in the context of a novel than the original route. Furthermore, the difference between the overlapping segments was similar to the difference observed for the non-overlapping segments, i.e., an old route segment in the context of a novel route was processed as if it were an entirely novel segment. We discuss the results in relation to binding, chunking, and transfer effects, as well as potential practical implications.

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Introduction

Imagine the following scenario: a driver is driving down the same fixed route for the past week, month or year. Due to road works, the route is diverted, so that for the next several turns she must travel a new route which partially overlaps with the original route; e.g., from BLOCK[1] three to BLOCK six the novel route is exactly the same as the original route. While we expect that the driver will not show the same level of proficiency on the new parts of the novel route, what about the old parts of the novel route, those overlapping with segments of the old route? Will

[1] BLOCK (upper-case) refers to a segment connecting two intersections, whilst block (lower-case) refers to a group of experimental trials).

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these overlapping route sections, which are the same for both the old familiar route and the novel route, be treated with the same proficiency? This possibility is intuitive, yet research into chunking reveals an alternative, striking possibility. Namely once a (route) sequence has been sufficiently learned and its representation is unitized, the individual elements comprising it cease to play a role in performance (e.g., see Perlman, Hoffman, Tzelgov, Pothos & Edwards, 2016). Accordingly, specific route information, e.g., "turn right at this corner", may only exist in the context of a given familiar route and cease to exist from a performance perspective when the very same information (e.g., making the same right turn at the same corner) is presented in the context of a different route.

This question, in addition to having theoretical value as elaborated below, applies to a multitude of route learners, who as opposed to, e.g., taxi drivers, typically follow a fixed route when going from point A to point B, such as mailmen, milkmen, lorry drivers, or GPS-guided driving. In such cases, the development of a cognitive map, where the entire geographic area is represented, is less feasible. For example, the first author recently visited London, where he asked a bus driver if he drives close to a certain street, and the bus driver replied that he had "no idea". Fixed route learning may involve different processes at the neural level as well. For example, London bus drivers (fixed route) had smaller hippocampal volume than did taxi drivers (non-fixed route), who were matched for mileage and stress (Maguire, Woollett, & Spiers, 2006).

Typically, route learning is assumed to occur by non-unitized item-specific information. Paths, edges, districts, landmarks, etc. have been suggested as important cues in route learning (Epstein, & Vass, 2014, Gillner & Mallot, 1998; Kuipers, 1978, 2000; Kuipers, Tecuci, & Stankiewicz, 2003; Meilinger, 2008, Meilinger, Frankenstein, & Bülthoff, 2014; Werner, Krieg- Brückner, & Herrmann, 2000). Additional information corresponds to direction-based strategies, which may rely on information about angular direction at different locations to the final destination, has also been shown to play a role in route learning (Bailenson, Shum, & Uttal, 2000; Fu, Bravo, & Roskos, 2015; Hochmair & Frank, 2002; Sakellaridi, Christova, Christopoulos, Vialard, Peponis, & Georgopoulos, 2015). Another plausible approach was suggested by Newell and Simon (1972), whereby arriving at the intended location involves incremental optimization, which is similar to cued recall, whereby one step informs the next (Newell & Simon, 1972). While these theories have substantial differences, they all focus on item-specific information, such as a direction, an angle, or a previous step informing a later response. Recently, the notion that route learning is more complex than just simple stimulus response associations and may actually be represented in a unitized manner has been noted (Strickrodt, O'Malley & Wiener, 2015; see also Klippel, Tappe, & Habel, 2003; Richter, & Klippel, 2005). Here, we extend this notion to empirically address if route unitization, like other forms of unitization typical of the sequence learning domain, renders item-specific information less relevant.

While in some of the reviewed studies, participants were required to move through space, our task involved following a moving dot across a map. Accordingly the spatial learning processes may not be exactly the same. Note, the current design is no less ecological as it is typical of many current navigation applications (e.g., google maps). Further note that this design is compatible with the current goal of addressing if the motor sequence corresponding to spatial responses could be chunked into a unitized representation.

Chunking, one of the most basic processes of the cognitive system (e.g., Boucher & Dienes, 2003; Goldstone, 2000; Knowlton, & Squire, 1996; Miller, 1956; Rosenbaum, Hindorff, & Munro, 1987; Rosenbaum, Kenny, & Derr, 1983; Simon, & Barenfeld, 1969) relates to how elementary units can be bound together in aggregate chunks. In sequence learning (e.g., Cleeremans & McClelland, 1991), for example, the notion of chunking is central and refers to a situation where adjacent stimuli in a fixed sequence may eventually be chunked into a single unit. Chunking is a *hierarchical* process, where individual items (e.g., A, B, C, and D) form sub units (e.g., AB, CD), which go on to form a single chunk (ABCD) representing an entire sequence (Perlman, Pothos, Edwards & Tzelgov, 2010). Chunking, as a process, necessitates a fixed order (Perlman, et al., 2010, 2016). The underlying assumption in chunking is that, as elementary units co-occur, larger units build up. Such an analysis is motivated from associative learning theory and has been embodied in important research traditions, such as that of connectionism (e.g., Elman, 1990; Rumelhart, & McClelland, 1986).

When a fixed route is practiced repeatedly, we suggest that it may be viewed as a sequence (e.g., Meilinger, 2008), in the simple sense that individual route segments (e.g., turn right, go left, right and then right) form a sequence. In effect, knowledge of this sequence constitutes route knowledge (Meilinger, et al., 2014). Accordingly, as in other sequence learning paradigms (e.g., Perlman, & Tzelgov, 2006; see also Perlman, et al., 2016), after learning is acquired, the emphasis may no longer be on specific information, e.g., landmarks, individual turns or cues, but rather on a process of sequential compression (or chunking). The spatial information of represented route is compressed into a single unit of information. For example, consider a route that requires three turns to arrive at a location. Initially, there are three parts of information to process (i.e., turn right, turn left, turn right) whose processing may well be aided by landmarks. Once the entire sequence is learned, the information is compressed (or chunked) into a single unit of information (e.g., “route X”). Showing that fixed-route learning follows the pattern of typical sequence learning would indicate that it is an instance of a broader sequence learning domain.

Moreover, addressing route learning as a chunking process links such learning with other basic processes of the cognitive system, such as development of expert knowledge (e.g., Simon, & Barenfeld, 1969), category learning (e.g., Goldstone, 2000; Knowlton, & Squire, 1996), working memory (e.g., Miller, 1956), motor control (e.g., Rosenbaum, Hindorff, & Munro, 1987; Rosenbaum, Kenny, & Derr, 1983) and control of complex and dynamic situations (Vallacher, & Wegner, 1987). Such a link suggests that in route unitization, like other forms of chunking, participants cease to make use of smaller units (Perlman, et al., 2010) e.g., making a specific left turn following a previous right turn. That is, after unitization develops, such item-specific route information would no longer play a role when traversing the route. Others maintain that representation of smaller units actually may disappear or *decay* (see also, e.g., Giroux, & Rey, 2009; Perruchet, Vinter, Pacteau, & Gallego, 2002; Perlman, et al., 2016; Pothos, & Wolff, 2006). In any case, these studies agree that item-specific information no longer plays a key role in performance after the learnt information becomes unitized into a single representation. Thus, even if full decay of item-specific information does not ensue, for all intents and purposes such information is not utilized in performance. Accordingly, our research question is: if once the entire fixed route is learned, will the individual route parts become unitized, thereby rendering the item-specific information irrelevant to performance? Note, we do not suggest that mapping, landmarks, angles, directions, and cued recall are not part of a route mapping process; they most clearly are. Rather, we ask whether a bias can arise in route recall, from the extant theory on unitization, according to which the unitization of route knowledge can eventually supersede representation of individual elements.

The present paradigm follows the theme outlined in the aforementioned driving example. Namely, we measured performance on an overlapping route segment, common to both a previously learned route (which always appears in red), and to a novel route (which always appears in blue). In other words, both the original red training route and the novel blue route contained the same overlapping route section. Participants were randomly divided into two groups; the sequential group who learned the entire route in sequence and the random group who learned individual route segments not in sequence. We consider whether participants in the sequential group would show different test performance for the very same overlapping route segments when presented in different contexts, i.e., the context of the old training route (red) and the new test route (blue).

Accordingly, we expect the following: First, test performance on the red original route should be overall better in the sequential-group than in the random-group. We further predict an overall advantage for the same overlapping route segment when performed in the context of the red route versus the novel blue route. We also critically predict a two-way interaction between group (sequential vs. random) and route (original vs. novel), so that only participants in the sequential group will demonstrate better performance on overlapping route segments performed in the context of the red (original) route versus the blue (novel) route. This latter interaction is compatible with a unitization account whereby the individual elements cease to play a role.

While the aforementioned result pattern relates to overlapping stimuli, results should be at least as robust in the non-overlapping BLOCKs. We focus on the *overlapping* BLOCKs in Experiments 1 and 2 for two reasons: First, only analysis of overlapping route segments can address unitization. Second, the non-overlapping BLOCKs could not be compared as they comprised different stimuli and responses (although see Experiment 3).

Experiment 1

Method

Participants

Thirty students (7 males, mean age = 22.9) from introductory psychology courses at Ben Gurion University participated in the experiment for course credit. All participants reported normal or corrected-to-normal vision.

Apparatus

The experiment was conducted using IBM compatible Pentium III computers with 17″ monitors. The screen was placed approximately 60 cm from the participants. Participants responded by keyboard press. The onset of a stimulus started the timer; the stimulus changed location (intersection) as soon as the participant responded. Responses were indicated by pressing the 1/0 keys (arrows pointing right/left were taped onto these keys). Participants were asked to use the index fingers of both hands for key presses.

Stimuli and procedure

The stimuli were all based on two routes, that we call the red and the blue routes. Each route comprised BLOCKs, i.e., segments connecting two nearest intersections. An 'intersection' is defined as a map location where one may make a turn. As shown in Fig. 1, there are seven BLOCKs connected by eight intersections in each route. The routes were depicted on a city map (Fig. 1) via a red line or blue line. At all times, both red and blue lines, indicating the two routes, were present, regardless of which route participants were responding to (this ensured saliency of the overlap between the two routes). During training only the red route was performed, but during test both the red and blue routes were performed. Indicating the route segments as BLOCKs 1–2, 2–3, 3–4, 4–5, 5–6, 6–7, and 7–8, we note that two BLOCKs (4–5 and 5–6) were the same in both routes. BLOCK 4–5 began at intersection 4 and extended to intersection 5, and BLOCK 5–6 began at intersection 5 and extended to intersection 6. Traversing this same overlapping route segment required exactly the same response to the same stimuli at the same location.

Training: Two groups of participants (sequential- vs. random-group) underwent extensive training on the red

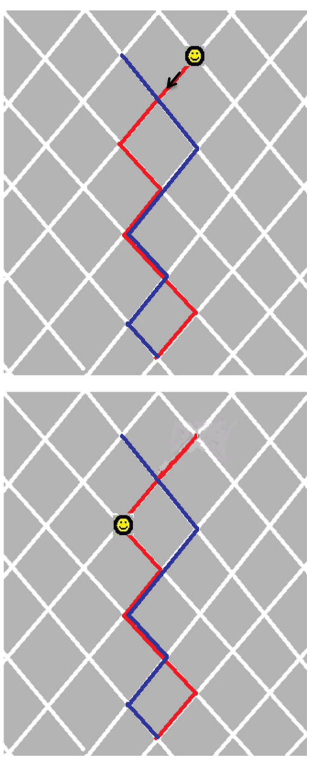

Fig. 1 *Upper panel* the stimuli employed in Experiment 1, which consisted of one learning route (*red*) and two test routes (the *same red route* along with a *novel blue route*). Navigation takes place from the *upper part* of the *map* downwards. Note that while only one route is being performed at any given time, both routes are shown throughout learning and test. Travel direction is indicated by the *arrow*. *Lower panel* an example of the third learning trial in Experiment 1. After participants have responded twice via arrow press, the smiley moves to the third intersection. The correct response for this third trial would be the *left arrow* (color figure online)

route shown in Fig. 1. Both groups were instructed to follow the entire red route by monitoring the movement of a smiley and making the appropriate (left/right) response. Following each response, the smiley would move to the next intersection. In the sequential group, the smiley appeared at the beginning of the route and participants had to follow it by arrow-response across the entire route in sequence. A Trial began with the smiley located at the beginning of the training route (intersection 1, Fig. 1), where the correct response would be pressing the left-arrow key. A depiction of the third trial is shown in Fig. 1, lower panel, where after responding to the first two trials, the smiley moves to the third intersection. The correct response for this trial would be the left arrow which would move the smiley to intersection four, and so on. Once the smiley reached the end of the route, it returns to the beginning and participants begun again. The direction of movement was always from top to bottom.

In the random-group, participants were exposed during training to individual BLOCKs along the red route, and never performed the entire route in sequence. Namely, the smiley appeared at random intersections across the route, participants made a single response (turn), upon which the smiley would randomly "jump" to another intersection. Some learning should occur even for the random condition, as at the very least, participants should gradually learn the correct responses to each intersection.

Training was comprised of 10 blocks,[2] each consisting of 105 trials (traversing 7 BLOCKs 15 times). The response stimulus interval (RSI) separating each sequence (of 7 responses) from each other was 1000 ms. During the RSI, the map appeared with no smiley. Participants did not receive feedback; the smiley jumped to the next intersection even after errors. Note that no feedback was necessary, since the red line, indicating the route, was continuously present on the screen and participants simply had to make the correct responses, at different intersections (indicated by the smiley).

Test: While participants did not perform the blue route during training, it was present, and thus participants during training saw that the overlapping route segment was common to both the red and blue routes. After training, participants in both groups proceeded to the same test, where they had to intermittently perform the old route (red training route) and a blue novel route in a random order. Performance was guided by the smiley which moved in a sequential manner from beginning to end. To reiterate, the only difference between groups was at training, where the random-group never performed the entire route in sequence. There were ten test blocks; each block comprised

[2] As explained above, block (lower-case) refers to a group of trials and not route segment (BLOCKS).

a red and blue route each appearing once yielding 140 trials. After each test route was performed, it was followed by an RSI of 1000 ms. During both training and test trials, participants had to respond, as fast as possible, by pressing the corresponding arrow key to the appearing smiley.

Results and discussion

The training results reveal improvement across training trials [$F(9, 252) = 54.69$, MSE = 13,871, $\eta_p^2 = 0.66$, $p < 0.001$], from a mean of 612 ms to mean of 351 ms in the experimental group and from a mean of 1008–699 ms in the control group. These group differences were significant across all blocks [$F(1, 28) = 335.29$, MSE = 217,918, $\eta_p^2 = 0.92$, $p < 0.001$], even in the last block [$F(1, 28) = 321.00$, MSE = 19,814, $\eta_p^2 = 0.91$, $p < 0.001$].

The key question of interest is whether a unitized representation developed, in a way that individual route segments may no longer be relevant. To answer this question, we focused on the differences between overlapping route segments performed in the context of the red and blue routes. Both RT and error data for all test trials were recorded. Comparable analyses were run on both of these measures, yielding similar results, except that some RT effects were not apparent in the error data. There was no evidence of a speed-accuracy trade-off, thus, only RT data from correct responses were included in the analysis and are presented in detail. Average error rates were 3.3 % for the sequential group and 2.4 % for the control group.

Test data: The median RT of each participant for each overlapping intersection was calculated across blocks and averaged across participants, see Fig. 2. These medians were submitted to a two-way mixed analysis of variance (ANOVA) with route (original/novel) and group (sequential/control) as between subject factors (Fig. 2).

Performance on the original red route was faster than on the novel blue route [$F(1, 28) = 8.402$, MSE = 968, $\eta_p^2 = 0.23$, $p < 0.01$]. Overall performance of the sequential group was marginally better than of the random group [$F(1, 28) = 3.781$, MSE = 5241, $\eta_p^2 = 0.11$, $p < 0.07$]. The critical Route by Group interaction was significant [$F(1, 28) = 12.734$, MSE = 968, $\eta_p^2 = 0.31$, $p < 0.01$]. Planned comparisons revealed a significant difference within the sequential group, whereby latency was faster when participants responded to the overlapping BLOCKs appearing in the context of the original (red) route than when responding to these very same route segments appearing in the context of the novel (blue) route [$F(1, 28) = 20.799$, MSE = 967.82, $\eta_p^2 = 0.42$, $p < 0.001$]. No such effect was found in the random-group ($F < 1$). Please see Fig. 2.

This main finding that RTs in the sequential group were shorter for the very same overlapping intersections

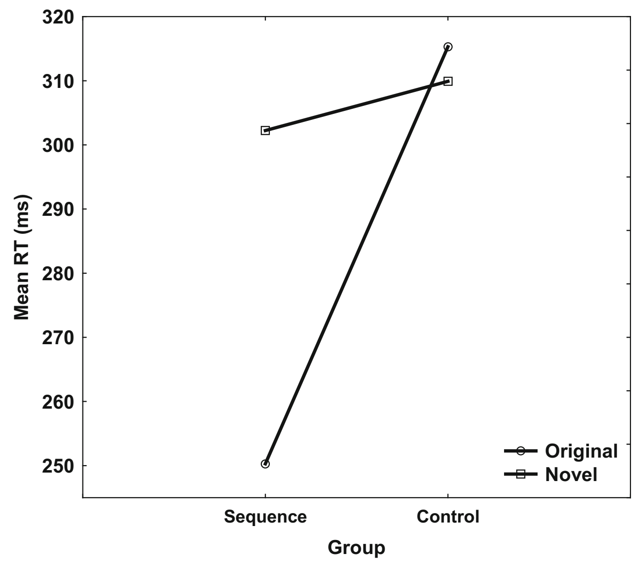

Fig. 2 Mean of median reaction times (RTs) for all test blocks of trials for the original and novel routes, in each condition of Experiment 1

(comprising BLOCKs 4–5 and 5–6) in the original route than in the novel route provides evidence for the type of unitization we hypothesized (see also Perlman, et al., 2016). This result suggests that item-specific information, which is necessary at least for initial performance, may be superseded, when a unitized representation for the entire sequence emerges (see also Vallacher, & Wegner, 1987).

It might be claimed that unitization was merely an efficient *strategy* in Experiment 1, which resulted in enhanced performance at test. Responding using individual item-specific information for both the blue (novel) and red (original) routes, would only benefit 2/7 responses (number of overlapping stimuli), while responding on the basis of a unitized representation would benefit the remaining 5/7 responses in the original red route (number of non-overlapping stimuli). Consequently, unitization rather than being obligatory may merely be a preferred strategy employed only when there is no (cognitive) reason to utilize item-specific information. Indeed, Perlman, et al. (2010) showed that an increase in sequence overlap renders unitization less likely. Yet Perlman et al.'s study concerned the *emergence* of unitization and not the application of the corresponding knowledge during test, after unitization was (presumably) generated. Nevertheless, motivated by these ideas, we can ask a similar question: assuming a unitized representation has already emerged, is it the case that it will be utilized when less efficient? Cognitively, as the overlap between a learned sequence and a novel one increases, perhaps it would make more sense to abandon a unitized representation and revert to item-specific information. The converse possibility is that, once a unitized representation has emerged, its use is *obligatory*, regardless of its efficiency in subsequent application of the corresponding knowledge (Perlman, & Tzelgov, 2006). In Experiment 2, we examine if the same result pattern would be observed when overlap increases to 3/7 (from 28 to 42 %).

Experiment 2

In Experiment 2, the degree of overlap between routes increased to include intersections 4, 5, and 6 (BLOCKs 4–5, 5–6, and 6–7, see Fig. 3). Observing the same pattern of results as in Experiment 1 would suggest that a unitized representation, once generated, will be employed in an obligatory way, such that it is not possible to discard it, even if it becomes less efficient to utilize.

Method

Thirty university students (7 males, mean age = 24.0) who did not take part in Experiment 1, participated in Experiment 2. The map used in this experiment is presented in Fig. 3. Aside from increased overlap this experiment was identical to Experiment 1.

Results and discussion

Visual inspection of the mean latencies in the various conditions presented in Fig. 4 show that the results of the experiment are broadly similar to those of Experiment 1. As before, to address how sequential vs. random (control) training affects performance, we focused on test performance. Regarding training, we briefly mention that there was evidence for improvement [$F(9, 243) = 27.01$, MSE = 25,146, $\eta_p^2 = 0.50$, $p < 0.001$], from a mean of 637 ms to a mean of 387 ms in the sequential group and from a mean of 1148–726 ms in the control random group. These differences between groups were also significant [$F(1, 27) = 82.03$, MSE = 1,110,335, $\eta_p^2 = 0.75$, $p < 0.001$]

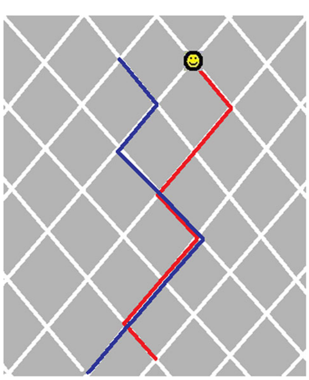

Fig. 3 The stimuli employed in Experiment 2

even in the last block [$F(1, 27) = 152.04$, MSE = 39,262, $\eta_p^2 = 0.84$, $p < 0.001$].

Both RT and error data for all test trials were recorded. Comparable analyses were run on both of these measures, yielding similar results, except that some RT effects were not apparent in the error data. As in Experiment 1, there was no evidence of a speed-accuracy trade-off, thus, only the RT data are presented in detail. Average error rates were 4 % for both groups. Only RTs from correct responses were included in the analysis.

As previously, for each participant, the median RT for each overlapping intersection was calculated for all blocks and averaged across participants, see Fig. 4. These medians were submitted to a two-way mixed analysis of variance (ANOVA) with route (original/novel) and group as a between subjects factor (Fig. 4). As previously, we focus on the interaction of group by route along with the accompanying simple main effects. While the random group should show no differences between performing the overlap route segments in the context of the two routes (original-red/novel-blue), the sequential group should show better performance for the overlapping BLOCKs in the context of the original route vs. the novel route.

The critical route with group interaction was significant [$F(1, 28) = 5.717$, MSE = 437, $\eta_p^2 = 0.16$, $p < 0.05$]. Planned comparisons reveal (see Fig. 4) a significant difference in the sequential group, where latency was faster when participants responded to overlapping BLOCKs appearing in the context of the original route than when responding to these very same BLOCKs when they appeared in the context of the novel (blue) route, [F(1,

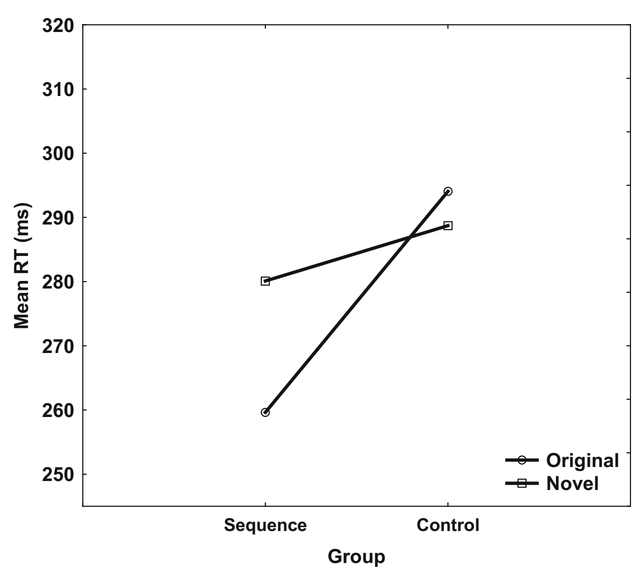

Fig. 4 Mean of median reaction times (RTs) for all test blocks of trials for the original and novel routes, in each condition of Experiment 2

28) = 7.193, MSE = 4370, $\eta_p^2 = 0.20$, $p < 0.05$]. No such effect was found in the random group ($F < 1$).

In both experiments, the sequential group responded faster to the very same overlapping route segments when they appeared in the context of the original route than when they appeared in the context of the novel route. Such results are consistent with unitization of route learning occurring only in the sequential group. Showing this same result pattern for increased overlap between routes where there is less utility for a unitization strategy is consistent with unitization being less of a strategy and more of an obligatory process that occurs regardless of overlap degree (Perlman, & Tzelgov, 2006). Once unitization develops, item-specific information, such as specific individual responses, may be less relevant to performance and execution of route knowledge (see also Perlman, et al., 2016).

In Experiments 1 and 2, a single route was employed at training and two routes at test. Participants learned a specific given red training route, and at test, performance of the same overlapping route segment was examined in both the context of this red route and in the context of a novel blue route. It is possible (although unlikely) that results may have been affected by this design. Also, having a single training route and a single novel route at test rendered impossible the comparison between overlapping and non-overlapping intersections. In Experiment 3, we ask whether the impairment in performing the overlapping route segment in a novel context is similar in magnitude to perform a new route segment (non-overlapping). In other words, is an old route segment appearing in a new context treated it as if it were a new route segment? Accordingly, Experiment 3 employed two counterbalanced routes, which were shown to be equally difficult, enabling comparisons between non-overlapping segments.

In addition, we rectified some limitations of the first two experiments. First, perhaps unitization effects are limited to relatively short routes comprising even shorter overlapping segments. Unitization has been shown to be limited in sequence learning paradigms to motor chunks involving only four or five elements (Ganor-Stern, Plonsker, Perlman, & Tzelgov, 2013; Verwey, Shea, & Wright, 2015). Thus, in Experiment 3, route length was increased to 15 intersections comprising an overlapping segment of six BLOCKs. Second, in Experiments 1 and 2, there were no landmarks that could cue participants. It can be claimed that unitization in route learning would be less necessary in the presence of landmarks, as learning can develop by associating turns to landmarks (Epstein, & Vass, 2014). Would evidence for unitization exist when landmarks are able to cue participants to familiar route segments? Demonstrating similar results even in the presence of salient landmarks would render the current claims more robust. Third, it might be claimed that showing the whole route on the screen continuously (as in Experiments 1 and 2) facilitated unitization. In Experiment 3, route presentation is limited by participants' progress. Finally, it could be claimed that showing both routes across training, which on the one hand is advantageous in rendering overlap more salient, may on the other hand have been disadvantageous. For example, it may have allowed for some passive learning of the route intended as novel. In Experiment 3, only the route that was performed was shown at any given time.

Experiment 3

The goal of Experiment 3 was to rectify the aforementioned points and to examine if an old route segment that appears in the context of a novel route is performed like a new (non-overlapping) route segment. Like previous experiments, unitization would be demonstrated by comparing performance for the same overlapping segments from the original and novel routes. If item-specific information is relevant to performance, participants would by definition recognize (at least show benefit for) the relatively long overlapping segment comprising the same stimuli, locations, and response. Consequently, making the same response sequence to the overlapping segment should be similar, regardless of route, even if it is not consciously recognized as overlapping. Yet if item-specific information is less relevant after unitization, the overlapping route segments should be responded to differently in the context of the training route than in the context of the novel route, this would demonstrate unitization of the training sequence. If this difference is similar to that observed between the non-overlapping segments of the original and novel routes, it would suggest that an old route segment presented in the context of a new route is akin to a novel stimulus.

Method

Participants

Thirty students (5 males, mean age = 25) from introductory psychology courses at Bar Ilan University participated in the experiment for course credit. All participants reported normal or corrected-to-normal vision.

Stimuli and procedure

The experiment was programmed in C++, and conducted with IBM compatible Pentium III computers and 17″ monitors. The screen was placed approximately 60 cm from the participants. Participants responded using the computer mouse. The aim of the participant was to follow a target along a route as shown in Fig. 5. Response times were recorded.

Unlike Experiments 1 and 2, in this experiment the route was not shown continuously during training, rather it was incrementally drawn, as participants progressed through task. Note, such a procedure is ecological, as in guided route navigation applications (e.g., Waze), the depicted route develops with one's progress. The stimuli are shown in Fig. 5a, b. The experiment was organized in 25 training blocks and 5 test blocks. At training, participants received one of two routes. Both routes comprised 15 intersections. Each of the two different routes (see Fig. 5) contained a common overlapping section comprising six BLOCKs. Half the participants were trained on route A, and half were trained on route B. Each training block consisted of 15 trials. Participants were instructed to follow a pink route-line by moving the Microsoft mouse cursor to a circle at the end of the depicted route segment (see Fig. 6). Upon a response, the circle moved to the next intersection. Accordingly, participants were required to "touch" the mouse cursor on the next circle, for the target to move on to the following intersection. For example (see Fig. 6), when moving from intersection 7–8, participants had to move the mouse along the pink-line, when the cursor touches intersection 8, the pink-line begins moving to intersection 9.

Two test routes, an original route and a novel route were presented intermittently in a random order. As in training, at test as well, performance was guided by tracking the route line with the mouse cursor (arrow, see Fig. 5).

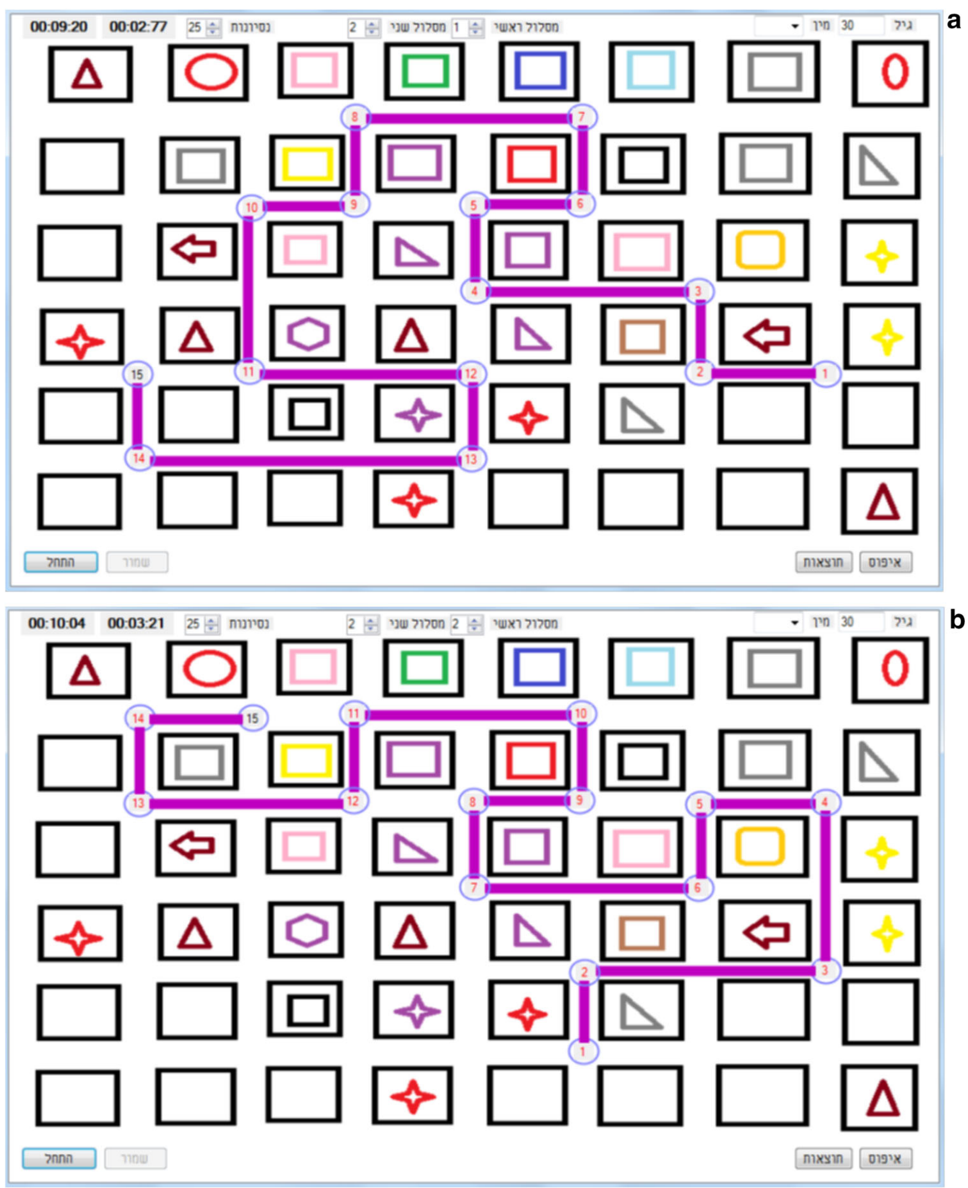

Fig. 5 The stimuli employed in Experiment 3 for routes 1 (**a**) and 2 (**b**). Note that the overlapping segment in route A (intersections 3–9) and route B (intersections 6–12) is exactly the same

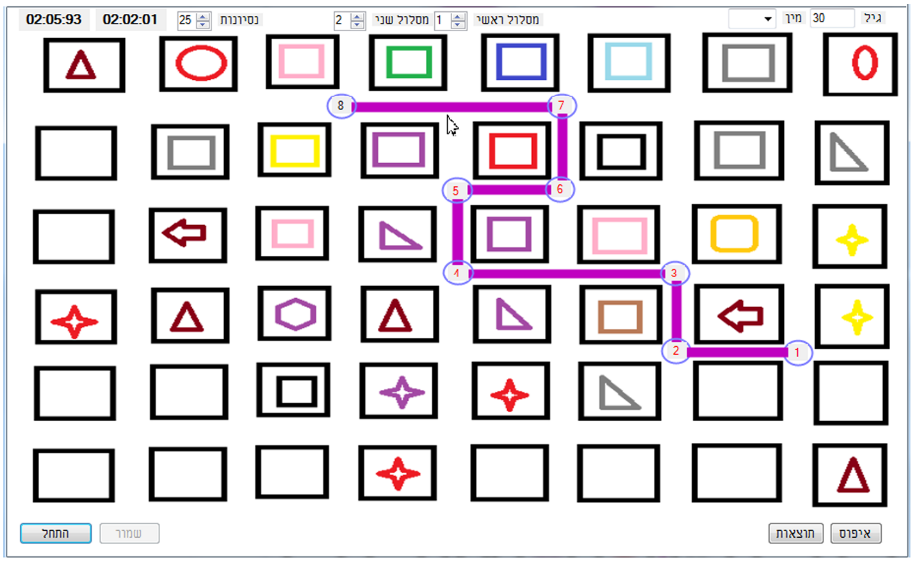

Fig. 6 Example of a learning trial for route 1 (Experiment 3). After responding to the seventh learning intersection by moving the mouse, the subject must move the cursor to the eighth intersection for the route to continue to intersection 9

Participants were required to respond as fast as possible. Each route appeared five times during test.

As opposed to both previous experiments where unitization was demonstrated by a group by route interaction, in Experiment 3 there was only one group. Accordingly, unitization should be demonstrated by a Route main effect (original vs. new), which should be significant even for the overlapping segments. Namely, the overlapping route segment in the context of a novel route should be performed significantly slower than in the context of the original route.

Results and discussion

We first checked that there were no overall differences in route difficulty: there was no significant difference across the learning trials between each of the two routes ($F < 1$), indicating that both routes were comparable. Likewise, learning performance for both the overlapping segments of these routes ($F < 1$) and the non-overlapping segments ($F < 1$) was statistically the same (Fig. 7).

The mean RTs of each test block of responses were submitted to a two-way analysis of variance (ANOVA) with route (original-route/novel-route) and overlap (overlapping/non-overlapping) as within subject factors. The overlap effect was significant [$F(1, 29) = 21.077$, MSE = 1215, $\eta_p^2 = 0.42$, $p < 0.0001$], indicating that the overlapping route segment was performed significantly faster than the non-overlapping route segment. As expected, the critical route effect was significant [$F(1, 29) = 26.591$, MSE = 829, $\eta_p^2 = 0.47$, $p < 0.0001$], indicating that participants performed significantly faster on the original route vs. the novel route. The Route by Overlap interaction was not significant [$F(1, 29) = 1.561$, MSE = 1596, $\eta_p^2 = 0.05$, $p = 0.22$], indicating that the observed performance advantage for the original vs. novel route evident in the non-overlapping condition was not statistically different than the same performance advantage evident in the very same overlapping route segments. Namely, performance of the non-overlapping route segment in the original route (443 ms) was faster than in the novel route (479 ms). Likewise, performing the overlapping segment in the original route was faster (423 ms) than performance of this very same segment in the novel route (441 ms). Furthermore, these differences were similar; the difference between overlapping segments performed in the context of the old vs new route was similar to the

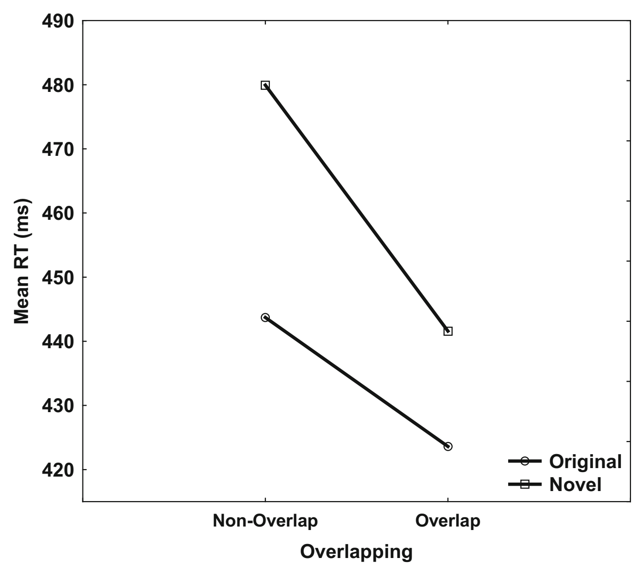

Fig. 7 Mean of median reaction times (RTs across test trials and blocks) for the original and novel routes in the overlap and non-overlap conditions of Experiment 3

difference observed between both routes in the non-overlapping route segments.

Unitization in the current experiment was demonstrated even when the length of the entire route and its overlapping segment was doubled. Demonstrating unitization for a segment of six overlapping elements appears to extend previous sequence learning findings where motor chunk size was limited to four or five elements (Ganor-Stern, et al., 2013; Verwey, Shea, & Wright, 2015). In addition, unitization occurred even when landmarks were available and could have been potentially used, and thus learning could have relied on item-specific representations by associating responses to landmarks (Epstein, & Vass, 2014). Note that landmark processing was not part of task requirement (Strickrodt, et al., 2015), e.g., turn left at the "big oak" Other studies however show that the mere presence of constant landmarks is sufficient to allow their processing in a manner beneficial to route learning (Foo, Duchon, Warren, & Tarr, 2007). Thus, while it is likely that landmark processing occurred, future research is required to discern if the obtained results apply to situations where intentional and associational landmark processing are part of task requirement. Finally, results indicated that an old route segment in the context of a new route is performed as if it were a completely new route segment.

General discussion

It is typically the case that route learning is assumed to depend on item-specific information such as angles, direction or turns (Gillner, & Mallot, 1998; Kuipers, 1978, 2000; Werner, et al., 2000; Kuipers, et al., 2003; Meilinger, 2008). Extending previous approaches (Strickrodt, et al., 2015), we have demonstrated here that, after sufficient learning, a unitized representation for a fixed route can emerge. That is, the sequence of elements comprising a route can be unitized. This unitized representation of a route sequence may suffice to guide an individual across the route, in an assumedly more efficient manner, compared to a disjointed non-unitized representation. Similarly, the motor behavior literature also indicates that people have the capacity to control short sequences of actions using chunks, whose elements can be treated collectively (Rhodes, Bullock, Verwey, Averbeck & Page, 2004; Sakai, Kitaguchi, & Hikosaka, 2003; Verwey, 1999, 2001; Verwey, Lammens, & van Honk, 2002, Verwey, & Wright, 2014). Additionally, in contrast to typical sequence learning paradigms where motor chunks represented subsequences with up to four or five elements (Ganor-Stern, et al., 2013; Verwey, Shea, & Wright, 2015), Experiment 3 demonstrates unitization of a long sequence consisting of 15 segments. Accordingly, unitization may be not as limited as previously supposed.

As mentioned, the current paradigm involving following a dot across a map may involve different learning mechanisms than route learning in some of the aforementioned route learning studies (e.g., Meilinger, et al., 2014), where one actually moves through space. Thus, additional research may be required before concluding that the current results straightforwardly apply to all forms of route navigation. In any event, this paradigm is ecological because it resembles navigation applications (Google-maps, Waze) where one follows a moving dot across a map.

While a process of unitization is known to be relevant to other sequence learning tasks (Perlman, et al., 2010), these experiments extend earlier results to the domain of procedural route learning. These results suggest a new angle in route learning and navigation, whereby route knowledge, similar to information from other sequence learning paradigms, can be represented in a high density fashion, where all item-specific information, e.g., a specific turn, is compressed into a single unit which cannot be readily unpacked. Thus, as in other domains (Perlman, et al., 2010, 2016), following unitization, the item-specific information that preceded learning may cease to be accessible or relevant. Consequently, individual elements no longer appear familiar as indicated by the increased RT for exactly the same turns in the overlapping segment when appearing in the novel route relative to the training route. This suggests that item-specific information of a given response (turn) may exist only in the context of a given route, and thereby would only be helpful when performing the same exact route.

Unitization may be advantageous because it reduces the amount of information necessary for representation, i.e., instead of maintaining a representation of seven or fifteen individual turns, one may represent an entire route as a single representation, e.g., "route x", thereby reducing cognitive load. As the route becomes unitized, it constitutes a single object in working memory and thus presumably its representation is less demanding, as opposed to representing seven or fifteen individual units of information. Research by Bo and Seidler (2009) as well as Seidler, Bo, & Anguera (2012) support the link between unitization and working memory. Another advantage of unitization is that the output, such as route navigation, may be performed automatically; there is no need to consciously retrieve the relevant information (see Ganor-Stern, et al., 2013 for such an account).

Viewing route learning as an automatic execution of a motor sequence does not belittle the importance of item-specific information. On the contrary, we believe, in line with other prominent models such as the ACT-R (Adaptive Character of Thought-Rational, Anderson, & Matessa,

1997) theory, that typical learning initially relies on item-specific declarative information ("at the big oak tree turn left", "when you reach Macy's turn right"). However, with practice, a route sequence may gradually become unitized and less reliant on item-specific information, as is the case with other types of skill learning (see Anderson, & Matessa, 1997). It is interesting to note that, even in the superficially simple examples in the present experiments, an algorithm that qualitatively reproduces our results would not be straightforward. Such an algorithm would still need to be context-dependent, that is, allow for the fact that exactly the same stimuli may be responded to differently in different contexts (for illustration, in "Appendix 1" we consider some simple examples of corresponding algorithms).

Sequence learning may lead to sequence knowledge consisting of associations between the stimuli (Mayr, 1996), responses (Willingham, Wells, Farrell, & Stemwedel, 2000), response–stimulus compounds (Ziessler, 1998) or stimulus–response compounds (Schwarb, & Schumacher, 2010). The present results demonstrate that these narrow associations consisting of *two* elements are not driving current performance. Associations between two locations were not relevant to performance, thus something more is needed to explain learning. Accordingly, we would expect that drivers who drive along a fixed route may perform their daily driving in an automatic fashion, and so they would not be confused by changing landmarks (e.g., removal of the oak tree, or relocation of Macy's). Clearly, there is a trade-off between robustness of the route knowledge and inflexibility, in cases when route variations are expected. Moreover, automaticity of a unitized representation may also produce disadvantages in performance, as changes in a sequence would be more difficult, once a route is unitized. For instance, think of a situation where one frequently travels from X to Y via route A in 80 % of circumstances, then one day wishes to travel from X to Y via route B, but wrongly takes the turn A instead. As the route sequence (X to Y via A) is a single unit (or decision), more cognitive resources may be needed to be allocated for properly traveling from X to Y via B (this extra processing is manifest through time latencies in classic unitization studies).

In the current study, participants learned the route in a guided manner, a manner of route learning that is highly relevant for everyday life, due to the increasing popularity of navigation aids based on the global positioning system (GPS). Indeed while guided learning may produce fewer errors than non-guided route learning, less spatial awareness may ensue as a result of guided route learning (Li, Zhu, Zhang, Wu, & Zhang, 2013). The implications of the current study pertain to fixed routes. Other disadvantages have been documented for guided vs. non-guided walking (Ishikawa, Fujiwara, Imai, & Okabe, 2008).

Along with the many advantages of a unitized route representation, the current aforementioned *possible* disadvantage has implications for transfer. The rigidity of unitized knowledge may generate a situation of non-transferable learning where knowledge about an overlapping route section in one context will not transfer to another route. Such skill learning may remain specific, as observed for example in sequence learning (Sanchez, Yarnik, & Reber, 2014), perceptual tasks (e.g., Karni & Sagi, 1991) or motor tasks (e.g., Pashler & Baylis, 1991). Conversely, a non-unitized representation should transfer from one context to another, as in the cases of pilots benefiting from a simulation of a flight experience (Gopher, Weil, & Bareket, 1994). Transfer of learning has been a central theme in both cognitive psychology and practical training courses. The current results can be viewed in this light, as an absence of transfer, namely, knowledge of the overlapping same turns did not transfer from the training route to the novel route. The current lack of transfer may differ from that in related situations, namely, as everything about these overlapping stimuli in the present experiments was identical (e.g., stimuli, location, and responses), still the same stimuli were responded to faster in the context of the familiar route versus the novel route. Perhaps transfer would have occurred if the learning procedure varied, and thus item-specific information would not have been tied exclusively to a given context, e.g., a given route (Perlman, et al., 2016; see also Green, & Bavelier, 2008, for a similar claim). Accordingly if from the beginning of training, turns along a given route are equally traveled in the context of other routes, transfer may be more likely. More research is needed to investigate this interesting topic.

Compliance with ethical standards

Funding This study was not funded.

Conflict of interest The authors declare that they have no conflict of interest.

Ethics All procedures performed in the reported studies were in accordance with the institutional ethical committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

Appendix 1

Simple algorithms for modeling sequence learning: We ask what kind of simple algorithms could, in principle, describe performance in our experiments and, specifically, the key finding that the overlapping stimuli were responded to differently in the context of a practiced sequence than in isolation. These algorithms are clearly not cognitive models, but still they may be useful in that they illustrate the algorithmic complexity of the obtained results. For example, imagine one needs to program the order of operations for a robot from 1 to *n*. This can be done in several ways, A–D.

A:

```
If 1 than 2
If 2 then 3
If 3 than 4
```

In this (A) situation after 1, 2 has to appear. Even when a robot performs Action 2 after (say) 6 rather than after the Action 1, it knows to proceed to Action 3. In B, if 2 appears, then 3 may not necessarily appear, rather, only if 1 and 2 appear in sequence will 3 follow.

B:

```
If 1 than 2
If 1 & 2 than 3
If 1 & 2 & 3 than 4
```

C:

```
If 1 then 2
    If 2 then 3
        If 3 then 4
        End if
    End if
End if
```

D:

```
If x=1 then 2
Else if x<n then x+1
Else if x=n end
```

In C and D situations, Action 3 must appear after Action 2 that follows Action 1. In Situation C for example, when the robot performs Action 2 after (say) Action 6 rather than after the first action, it does not know that it has to continue to Action 3. If the robot in situation D performs Action 6 and then 3, it will correctly infer Action 4. Yet even in such a case the robot does not seem able to reproduce the obtained behavioral results, as the overlapping segment is performed differently in the original and novel routes. The very same route sequence is performed differently by the cognitive system according to the route context it appears in.

One of the possibilities that arise from this study is that during training, there is a transition from declarative memory of separate connections between the locations from 1 to *n*, that is as in A, to procedural and automatic execution where Action 1 leads to Action 2 which leads to Action 3 which leads to 4 as in B, C and D. If one preforms the route in an automatic manner as a unit, but at some point transfers to a different route that partly overlaps with the old route, performance must revert again to declarative memory of separate connections between the locations.

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