The impact of cognitive aging on route learning rate and the acquisition of landmark knowledge

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Abstract

Aging is accompanied by changes in general cognitive functioning which may impact the learning rate of older adults; however, this is often not controlled for in cognitive aging studies. We investigated the contribution of differences in learning rates to age-related differences in landmark knowledge acquired from route learning. In Experiment 1 we used a standard learning procedure in which participants received a fixed amount of exposure to a route. Consistent with previous research, we found age-related deficits in associative cue and landmark sequence knowledge. Experiment 2 controlled for differences in learning rates by using a flexible exposure learning procedure. Specifically, participants were trained to a performance criterion during route learning before being tested on the content of their route knowledge. While older adults took longer to learn the route than younger adults, the age-related differences in associative cue knowledge were abolished. The deficit in landmark sequence knowledge, however, remained. Experiment 3 replicated these results and introduced a test situation in which a deficit in landmark sequence knowledge yielded an increased likelihood of disorientation in older adults. The findings of this study suggest that age-related deficits in landmark associative cue knowledge are attenuated by controlling for learning rates. In contrast, landmark sequence knowledge deficits persist and are best explained by changes in the learning strategy of older adults to acquire task essential associative cue knowledge at the expense of supplementary sequence knowledge.

Keywords: aging; route navigation; spatial cognition; learning

General Introduction

Route navigation is the most frequent daily navigation task. While many studies have shown that route learning abilities decline with the typical aging trajectory (for reviews see Lester et al., 2017; Lithfous et al., 2013), age-related changes in learning rate are often not accounted for. The result is that whilst we have a good understanding of age-related differences in the learning of a novel environment, our understanding of the final content of route knowledge possessed by older adults after a route has been successfully learned is limited. In this study we first compared route knowledge between young and older adults after limited exposure to a route. In the second experiment, we compare route knowledge between young and older adults after participants had successfully learned a route. In the last experiment, we investigated the impact of age-related differences in the final content of route knowledge on the wider navigation ability of older adults.

Frameworks of spatial knowledge acquisition suggest that early stages of learning involve the encoding of distinctive visual environmental features as landmarks (Chrastil, 2013; Foo et al., 2007; Siegel & White, 1975). In route learning, these landmarks are used as cues to execute the required motor response for successful navigation (Foo et al., 2005), which is known as the associative cue strategy (Waller & Lippa, 2007). This associative cue knowledge requires stimulus-response learning (S-R; Trullier et al., 1997) in order to bind directional information to landmarks (e.g. turn left at the church). Importantly, S-R information is not always held in isolation but can be linked to the up-coming landmark which will be encountered at the next intersection as stimulus-response-stimulus associations (S-R-S; Strickrodt et al., 2015; Trullier et al., 1997), for example "turning left at the church brings you to the post office". These S-R-S associations are thought to form the basis of route sequence knowledge which allow the navigator to generate expectations about the next location to be encountered and prepare responses (Schinazi & Epstein, 2010; Trullier et al., 1997).

Older adults have been shown to perform worse than younger adults in tests of associative cue knowledge (Head & Isom, 2010; Hilton et al., 2019; Liu et al., 2011; Wiener et al., 2012; Zhong & Moffat, 2016) and landmark sequence knowledge (Head & Isom, 2010; Hilton et al., 2019; Wiener et al., 2012; Wilkniss et al., 1997) after a period of route learning. This cannot be attributed to a failure to learn landmarks, since older adults are able to engage attention at relevant locations (i.e. intersections; Hartmeyer et al., 2017; Hilton et al., 2019), select relevant environmental features as landmarks (Grzeschik et al., 2019), and recall them from memory at similar rates to younger adults (Cushman et al., 2008; Head & Isom, 2010). Instead, it has been suggested that older adults are impaired in the actual association of spatial information and landmarks (Zhong & Moffat, 2016), which is in line with a more general age-related decline in associative learning ability in older age (Associative Deficit Hypothesis; Naveh-Benjamin, 2000). Indeed, when learning routes, older adults tend to avoid the associative cue strategy where possible, in favour of encoding landmarks which are located in the direction of travel, so that the direction of movement is coded in the visual position of the landmark and does not need to be explicitly represented in memory (Wiener et al., 2013).

Whilst current research provides substantial insight into age-related differences in acquisition of route knowledge when learning novel routes, our understanding of the final content of route knowledge is limited. One contributing factor to this contrast is the nature of the methods used to assess route learning and knowledge. Typical route learning tasks first involve a learning phase, in which participants navigate or are passively transported along a route which they are instructed to learn. This learning phase is followed by a test phase in which participants are probed on their ability to repeat the route, and on the content of their route knowledge via tests of landmark memory, associative cue, and landmark sequence knowledge. In all the route navigation studies discussed so far, the learning phase involved a set number of times participants viewed or navigated the route, or a set time limit to explore the environment. This approach will henceforth be referred to as *fixed exposure learning*.

Fixed exposure learning yields two concerns centred around the fact that the content of participants' route knowledge is being compared whilst their actual ability to successfully navigate through the environment varies. It is important to highlight at this point that the ability to navigate a route does not indicate that a participant possesses an exact, known structure of knowledge for that route. For example, on the simplest level a navigator could solely encode a vector of turns to complete a route (e.g., left-right-left-straight-right). The content of that navigator's route knowledge would be more limited than an individual who acquired associative cue and/or sequence information about the places and landmarks they encountered. Considering the vast range of individual differences apparent in navigation ability (Hegarty & Waller, 2009; Weisberg et al., 2014), setting an arbitrary cut off for exposure during learning provides only limited insights into the final content of route knowledge once successful navigation would be achieved.

The first concern with fixed exposure learning can be summarised as the *under-training* of older adults. In most route navigation studies, it is the older participant group who are less able to successfully navigate the route at the end of the fixed exposure learning protocol. This demonstrates that they have not fully developed their route knowledge by that point. Indeed, many studies using a fixed exposure approach would not be able to determine if the older participants would eventually be able to successfully complete the navigation task, and whether the means by which they would do so were comparable to the younger participants. The second concern with the fixed exposure learning procedure is that younger participants may be *over-trained*. That is to say that participants who perform very well early on, but are required to continue the learning phase, may receive more exposure than is required to acquire only the knowledge they need to complete the route navigation task without errors. In subsequent exposures those participants may engage in supplementary learning of additional information about the route. This supplementary knowledge may then give the impression that younger adults acquired particular information that is required for successful navigation that older adults could not learn.

The concerns of under-training older adults and over-training younger adults arise from the differences in learning rates between the two age groups. Studies focusing on cognitive domains other than navigation find reduced learning rates for older adults, for example in sequence learning of visuospatial information (Turcotte et al., 2005). Older adults also acquire information slower on procedural memory tasks, notably when associative learning is involved (Vakil & Agmon-Ashkenazi, 1997), which is in line with the Associative Deficit Hypothesis (Naveh-Benjamin, 2000). Vakil and Agmon-Ashkenazi (1997) noted that age-related differences in learning rate must be considered alongside differences in baseline performance when characterizing the specific memory deficits associated with normal aging. Our study applies this notion in a navigation context, for the learning of landmark and route information.

There are several hypotheses as to why older adults acquire less information than younger adults in the same fixed time period. The Speed of Processing theory of aging (Salthouse, 1996) posits that the speed at which cognitive functions are performed decreases in older age. That is, the time available for later operations is reduced when the prerequisite functions occupy larger proportions of the available time window. The products of earlier cognitive functions may degrade during the extended time taken for subsequent processes to take place and as a result the final output may be incomplete. Park (2000) emphasises that "the effects of the slowed processing speed are hypothesized to be global and to have an impact on all aspects of cognition" (p.10). More recent evidence supports this assertion; Ebaid et al. (2017) used measurements from assessments of motor dexterity to statistically control for motor speed differences between older and younger adults when comparing response times on traditional measures of cognitive processing (subsets of the WAIS-IV, Wechsler, 2008). They reported that older adults still exhibited processing speed deficits when motor speed was controlled for, which is discussed as affecting a variety of domains including short-term visual memory, visual-motor coordination, visual discrimination, attention, and concentration.

Additionally, the Resource Deficit Hypothesis (Craik & Byrd, 1982) suggests that the pool of cognitive resources available to process information and to perform cognitive functions declines in older age. This pool is referred to as being attentional in nature but is also characterised more generally as "mental energy". As a result of declining resources, cognitive operations carried out by older adults are limited in quantity (as evidenced by reduced span, Brown, 2016). The resource deficit has been suggested as a possible mechanism underlying associative learning deficits (Craik, 2012; Craik et al., 2010; Naveh-Benjamin et al., 2005; Naveh-Benjamin & Kilb, 2014). Such a relationship between resource deficits and associative learning has also been suggested in route navigation. Zhong and Moffat (2016) argued that older adults may allocate a greater proportion of their cognitive resources to landmark encoding, but do so at the expense of forming S-R associations between landmarks and required movement directions, thus leading to poorer route navigation performance. This explanation was supported by the unintuitive finding that memory for landmarks correlated positively with navigation errors in older adults. Older adults focusing more resources on the earlier stages of spatial learning, specifically landmark encoding (Siegel & White, 1975), may explain why their performance on landmark memory tasks is often similar to younger adults (Cushman et al., 2008; Head & Isom, 2010).

Age-related differences in learning rates means that differences in route knowledge that are present during fixed exposure learning may not reflect the final content of route knowledge. There are a few studies which employed an alternative approach to the fixed exposure learning procedure. Those studies instead used a performance threshold for ability to navigate through the environment as the indicator of when to terminate the learning phase. In this case, the amount of exposure to the route may vary between participants, but at the end of learning all of the participants are matched on ability to successfully navigate through the environment. We will refer to this approach as *flexible exposure learning*.

Of the studies which employed a flexible exposure learning approach one unsurprising, but reassuring, consensus is that most older participants were able to pass the learning phase by meeting a performance criterion for successful navigation (Allison & Head, 2017; Craig et al., 2016; Grzeschik et al., 2019; O'Malley et al., 2018). However, these studies report differing patterns of results: two studies reported that older adults took a greater number of trials to initially learn routes and follow up tests of route knowledge did not uncover age-related differences in associative cue (Grzeschik et al., 2019; O'Malley et al., 2018) or landmark sequence knowledge (O'Malley et al., 2018). Conversely, two other studies reported no difference between age groups in the time taken to learn a route (Allison & Head, 2017; Craig et al., 2016). However, one of the studies found that older adults performed worse on both tests of associative cue and sequence knowledge (Allison & Head, 2017), whilst the other did not conduct such tests (Craig et al., 2016).

Grzeschik et al. (2019) did not directly test the ability to navigate the route, but rather used the associative cue test as the indicator for successful navigation, by repeating interleaved videos of the route and tests of associative cue knowledge. Thus, in their study, more learning trials to reach criterion only revealed that older adults were able to successfully learn associative cue knowledge, but it took them longer to do so. This result is in line with results from O'Malley et al. (2018) who also did not report age-related differences in associative cue knowledge once a route was learned. However, O'Malley et al. (2018) assessed route knowledge with ability to provide directions at intersections during learning. Their post learning test of associative cue knowledge showed only ~60% performance, indicating that this was not the sole type of information participants used to navigate the route. This result reinforces the notion that learning a route does not necessarily result in an exact structure of route knowledge and highlights that associative cue knowledge should not serve as the sole indicator of the ability to successfully navigate a route.

O'Malley et al. (2018) also reported age equivalence on the landmark sequence task. The studies by both Grzeschik et al. (2019) and O'Malley et al. (2018) suggest that older adults have reduced route learning rate, but that their final content of route knowledge is comparable to that of younger adults. Note however, that participants in both studies were aware of the nature of the follow up tests and could have altered their learning strategy accordingly, away from what they may have learned naturally during navigation, in order to solve the up-coming tasks (Naveh-Benjamin et al., 2007). Indeed, this may have been trivial also for the older participants as both studies used short routes with only four intersections. Such a strategy could explain why, despite equal route lengths, older participants took more trials to complete learning in the study by O'Malley et al. (2018), where there were more follow up tests, than in the study by Grzeschik et al. (2019).

In contrast, Allison and Head (2017) and Craig et al. (2016) used longer routes, and somewhat paradoxically reported no differences in the number of sessions taken to reach criterion for successful navigation. Such a finding could be due to the lack of precision in assessing ability to navigate during learning. Each learning session contained either two (Allison & Head, 2017) or three (Craig et al., 2016) exposures to the route before knowledge was assessed. It is possible that testing participants' ability to navigate the route only after learning sessions which containing several exposures is not sensitive enough to reveal any age-related differences in route learning rate, which is supported by the differences reported in studies using 'per exposure' testing (Grzeschik et al., 2019; O'Malley et al., 2018).

In addition to several exposures per learning session, Allison and Head (2017) and Craig et al. (2016) also had a minimum of two learning sessions (i.e. a minimum of 4-6 total route exposures). Therefore, whilst they addressed the concern of under-training by requiring all participants to reach the same performance criterion during learning, their procedure could result in over-training. That is, participants who learned the route on the very first exposure would have had 3+ additional exposures in which to engage in supplementary learning. Indeed, Craig et al. (2016) explicitly reported that more younger than older adults could navigate the route after the first learning session (3 exposures), but required them to complete the second learning session nonetheless. This over-training of younger adults could be responsible for the age-related deficits in associative cue and landmark sequence knowledge reported by Allison and Head (2017), which conflicts with O'Malley et al. (2018).

The present study investigated the content of route knowledge in older and younger adults following route learning via a fixed exposure learning procedure (Experiment 1) and a flexible exposure learning procedure (Experiment 2). The ability to navigate the route during learning was tested during each exposure (Grzeschik et al., 2019; O'Malley et al., 2018) and we used a moderately long route length (Allison & Head, 2017; Craig et al., 2016). We conducted follow up tests of landmark memory, associative cue knowledge, and sequence knowledge (Allison & Head, 2017; O'Malley et al., 2018) which participants did not know about during learning. We provide the first direct comparison of the fixed and flexible exposure learning procedures and thus of route knowledge acquired by younger and older adults during route learning and after route learning is completed. Our approach addresses both the concerns of under-training older adults and over-training younger adults.

Finally, we aimed to assess the impact of age-related differences in specific features of route knowledge when navigators are faced with a different task along the same route. Specifically, based on the findings of Experiment 2, we introduce a novel, realistic navigation task in Experiment 3 which requires a rich representation of the environment to be solved via a combination of landmark sequence and associative cue knowledge. Other than the addition of this task, Experiment 3 is a direct replication of Experiment 2 and the flexible exposure learning procedure, assessing the reliability of our findings in view of the variations in findings from previous studies using this approach (Allison & Head, 2017; Craig et al., 2016; Grzeschik et al., 2019; O'Malley et al., 2018).

Experiment 1

Introduction

The aim of Experiment 1 was to test whether we could replicate previous findings with our route learning protocol and our stimuli using a fixed exposure learning procedure. Such a conceptual replication is important to reinforce our arguments that (1) older adults will be less able to navigate the route by the end of the learning phase than younger adults and (2) that older adults will perform worse in tests of landmark associative cue and sequence knowledge. Additionally, the data from this experiment provides a route and procedure matched comparison to the flexible exposure learning approach used in Experiment 2.

In this experiment participants were required to give directional responses at decision points during the learning phase. The subsequent test phase comprised tests of landmark memory, associative cue knowledge, and landmark sequence knowledge. Based on previous research we expected: (i) Older adults to make more route navigation errors than younger adults (c.f. Head & Isom, 2010; Wiener et al., 2012). (ii) No significant performance difference between older and younger adults on the test of landmark memory (c.f. Allison & Head, 2017; Cushman et al., 2008). (iii) Younger adults to perform significantly better than older adults on the test of associative cue knowledge (c.f. Hilton et al., 2019; Zhong & Moffat, 2016). (iv) Younger adults to perform significantly better than older adults on the test of landmark sequence knowledge (c.f. Head & Isom, 2010; Wiener et al., 2012).

Method

Participants

Twenty-nine younger participants and 27 older participants took part in this experiment. Older participants were screened for mild cognitive impairment using the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005). All older participants scored above the MoCA cut off score of 23 (Luis et al., 2009; Waldron-Perrine & Axelrod, 2012). Table 1 summarises the demographic data of the final participant groups. Ethical approval was granted by the Bournemouth University Research Ethics Panel and written informed consent was gained from all participants who either received course credits or a monetary compensation for their time.

Table 1 - Participant demographics.

	Sex		Age		MoCA	
		n	Mean	SD	Mean	SD
Younger	Female	16	22.38	4.84		
	Male	13	19.69	1.11		
Older	Female	14	71.14	5.87	26.36	2.06
	Male	13	70.77	3.40	26.08	2.22

Design

The independent variables were age group (2 levels: younger and older) and for the learning phase, learning trial (1-3). The younger age group was 18-35 years old and the older age group was 65+ years old. There were a series of dependent variables: learning phase performance, landmark recall memory, associative cue knowledge, and landmark sequence knowledge.

Virtual Environment

We used a modified version of the environment described by Grzeschik et al. (2019), which was created using 3D Studio Max (Autodesk Inc., San Rafael, USA). The only change we made to the environment was to the landmarks at the intersections. We used two identical landmarks at each intersection, which were the only way to distinguish between different intersections (see Figure 1). The paths between intersections were all visually identical and of equal length.

We recorded videos of passive transportation for left, straight and right turns at each intersection. To generate routes for participants, we stitched a series of videos together in OpenSesame, an open source experiment presentation software (Mathôt et al., 2012). The routes consisted of 12 intersections (4 left turns, 4 right turns, 4 straight ahead). Every participant saw the same landmarks and could only ever see one pair of identical landmarks at a time. The order of landmarks and route directions were randomized for every participant. Routes were presented on a BenQ XL 2411-8 24-inch monitor at a resolution of 1920x1080p.

Learning Phase

Participants were passively transported along the route, which they were instructed to learn. During this passive transportation, the video was paused at each intersection so that movement along the route halted, and participants were required to indicate the direction of travel they thought would continue along the route using the directional keys on the keyboard. As soon as a response was given, transportation continued along the route regardless of the movement direction provided by the participant, thus providing participants with immediate feedback. Participants were informed that the route transportation always continued in the correct direction, even if their response was incorrect, and thus they could learn from the feedback. All participants navigated the route using this procedure three times sequentially during the learning phase. During the first of the three route exposures participants were required to guess their responses, since they had not seen the route before.

Figure 1 - A screenshot of an intersection in the environment.

Test Phase

Test phase tasks were not conducted using a computer. Participant responses were given verbally and recorded by the experimenter. The test phase comprised of three tasks:

Free Landmark Recall Task

This task was designed to assess memory for the landmarks along the route. Participants were asked to verbally recall as many of the landmarks as they could remember in any order (i.e. immediate free recall). Any ambiguous responses were clarified with the participant by asking for alternative names and visual descriptions of the object. Participants scored 1 for every landmark they recalled and 0 for every landmark they omitted.

Associative Cue Task

This task was designed to assess whether or not participants had associated a directional response to the landmarks along the route. Images of all the landmarks were printed out and shown to the participants individually and in a random order. Participants had to indicate the direction taken when this landmark was encountered along the route (the response was 3-alternative forced choice: left, right, and straight). Participants scored 1 for every correct response and 0 for an incorrect response.

Landmark Sequence Task

This task was designed to assess participants' knowledge of the sequence in which landmarks were encountered along the route. Participants were given all printed images of the landmarks and were required to arrange them in the order in which they were encountered along the route. This was a free reconstruction of order (ROO-free) task as described in Ward et al. (2010), in which participants are free to place landmarks into their positions in any temporal order. They were also free to change their decisions before finalising the sequence. The sequence was recorded once participants indicated they were finished.

We analysed the Sequence Task data in two ways. In the primary analysis we used absolute scoring. Each landmark placed in the correct position was scored 1 and each incorrectly placed landmark was scored 0 (c.f. Ward et al., 2010). Whilst this scoring method does indicate sequence knowledge in terms of absolute position, it is not sensitive to relative ordering of landmarks. For example, a participant could place N-1 items correctly, and then place the last landmark in position one, therefore shifting all items one place forward. This situation would result in a total score of 0, despite having the relative sequence of 11/12 landmarks in the correct order. To account for relative positioning, we calculated the Levenshtein Distance between the given sequence and the correct sequence (Levenshtein, 1966). The Levenshtein Distance is the number of moves required to transform the given sequence into the correct sequence. Moves consist of deletions, insertions and substitutions. Sequences with good relative ordering of landmarks will have lower Levenshtein Distances than those which have poor relative ordering.

Procedure

Participants first completed the Learning Phase. They were not informed about the nature of the tasks in the Test Phase to avoid any intentional changes in learning strategy. Once participants completed the Learning Phase, they immediately performed the Free Landmark Recall Task. The Free Landmark Recall Task was always performed before the other tasks because the other tasks involve showing the landmarks to participants which would confound landmark memory. The order of the Associative Cue Task and the Landmark Sequence Task was counterbalanced between participants and age groups to control for potential interference on memory.

Results

We analysed the data using logistic generalized linear mixed effects models (GLME) in R (R Core Team, 2019) using the lme4 package (version 1.1-14; Bates et al., 2015). We fitted our models using the procedure described in Bates et al. (2018). We began with the maximal models which reached convergence. We then iteratively reduced model complexity using principle component analysis (PCA; R-package: RePsychLing) to remove random effects components which accounted for the least variance until we reached the least components needed to still capture 100% of the variance explained. The resulting model was compared to a model with an intercept only random effect structure from which we selected the final model based on the Akaike Information Criterion.

Learning Phase

Figure 2 shows the percentage of correct directions given in each trial of the learning phase. In the first learning trial, older adults (mean: 35.49%, 95% CI: 40.95%, 30.04%) and younger adults (mean: 37.36%, 95% CI: 43.50%, 31.21%) performed close to the chance level of 33% (given the three possible movement directions at each intersection) since this was their first exposure to the route.

We used a GLME model with age group (factor, younger or older, centred using sum contrast coding) and trial (factor, 1 or 2 or 3, coded using successive differences contrasts) as fixed effects, and participant and stimulus as random effects. The outcome variable was performance, which is whether the response given at each intersection was correct (1) or incorrect (0). Estimates, standard errors, z-values, and p-values for the Learning Phase model[1] are reported in Table 2. The model shows that younger adults performed better than older adults, and that performance improved from trial 1 to 2, and trial 2 to 3 (see Figure 2). The only significant interaction was age group (younger vs older) x trial (1 vs 2) which shows that the size of the age group effect increased from trial 1 to 2.

Table 2 - Coefficients from the Learning Phase GLME analysis.

Fixed effect on Learning Phase performance	Estimate	Std. error	z-value	p-value
Intercept	0.43	0.11	3.82	<.001*
Age group (older vs younger)	0.29	0.09	3.10	.002*
Trial (1 vs 2)	1.33	0.12	10.97	<.001*
Trial (2 vs 3)	0.45	0.12	3.55	<.001*
Age group (younger vs older) * trial (1 vs 2)	0.28	0.12	2.29	.022*
Age group (younger vs older) * trial (2 vs 3)	0.20	0.13	1.58	.113

*Significant p values (|p|<0.05)

[1] Learning Phase GLME model as expressed using the lme4 package:
glmer(performance ~ age_group * trial + (1|participant) + (1|stimulus), data = data, family = binomial)

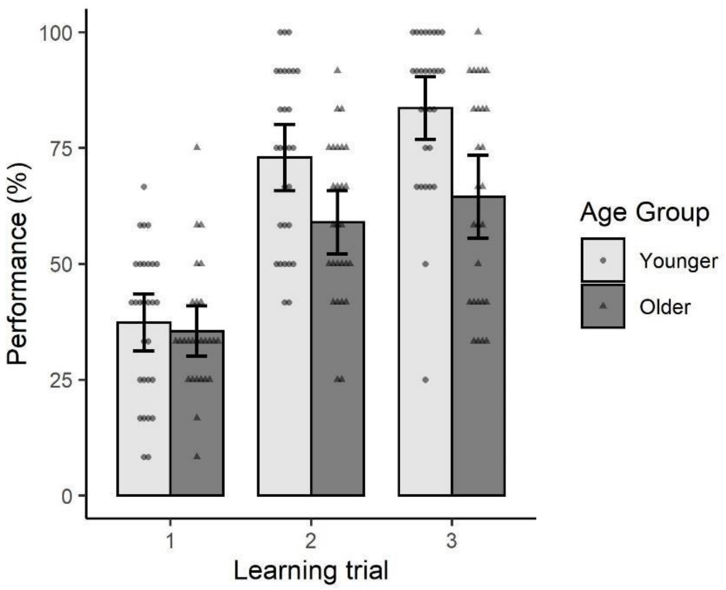

Figure 2 - Average performance in each learning trial for the younger and older participant groups. Bars are group means, points are individual participants and error bars are 95% confidence intervals.

Test Phase

Each model[2] included age group (factor: younger or older; centred using sum contrast coding) as a fixed effect and participant and stimulus (landmark) as random effects. The outcome variable for all models was performance which is whether each response given was correct (1) or incorrect (0).

[2] GLME model as expressed using the lme4 package:
glmer(performance ~ age_group + (1|participant) + (1|stimulus), data = data, family = binomial)

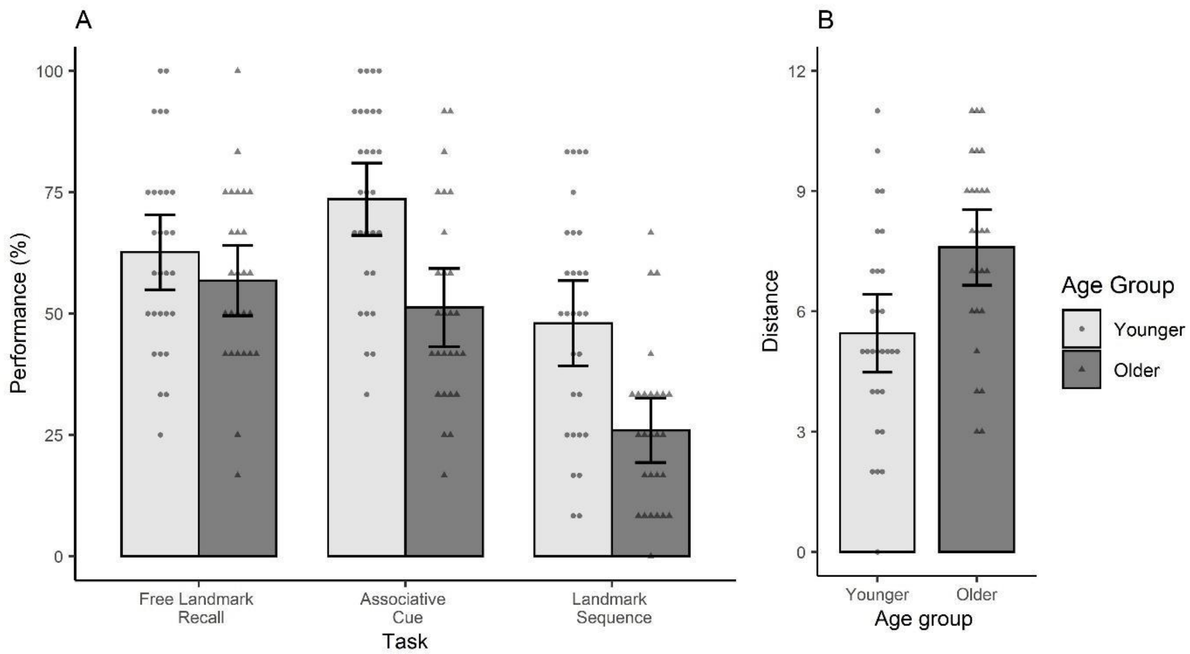

Figure 3 - (A) Average performance in each test task and (B) Levenshtein distances for the Landmark Sequence Task for the younger and older participant groups. Bars are group means, points are individual participants and error bars are 95% confidence intervals.

Free Landmark Recall Task

Estimates, standard errors, z-values, and p-values for the Free Landmark Recall Task model are reported in Table 3 and show that age group was not a significant predictor of performance (see Figure 3a).

Table 3 - Coefficients from the Free Landmark Recall Task GLME analysis.

Fixed effect on Free Landmark Recall Task performance	Estimate	Std. error	z-value	p-value
Intercept	0.46	0.19	2.42	.016*
Age group (older vs younger)	0.14	0.12	1.18	.240

*Significant p values (|p|<0.05)

Associative Cue Task

Estimates, standard errors, z-values, and p-values for the Associative Cue Task model are reported in Table 4. Age group was a significant predictor of performance, with younger participants performing better than older participants (see Figure 3a).

Table 4 - Coefficients from the Associative Cue Task GLME analysis.

Fixed effect on Associative Cue Task performance	Estimate	Std. error	z-value	p-value
Intercept	0.64	0.20	3.26	.001*
Age group (older vs younger)	0.58	0.14	4.01	<.001*

*Significant p values (|p|<0.05)

Landmark Sequence Task

Absolute Scoring

Estimates, standard errors, z-values, and p-values for the Landmark Sequence Task model are reported in Table 5. Age group was a significant predictor of performance, with younger participants performing better than older participants (see Figure 3a).

Table 5 - Coefficients from the Landmark Sequence Task GLME analysis.

Fixed effect on Landmark Sequence Task performance	Estimate	Std. error	z-value	p-value
Intercept	-0.63	0.14	-4.41	<.001*
Age group (older vs younger)	0.54	0.13	4.08	<.001*

*Significant p values (|p|<0.05)

Levenshtein Distance

We calculated Levenshtein Distances using the stringdist package (van der Loo, 2014) version 0.9.5.2 (2019) in R (R Core Team, 2019). A Welch's two sample t-test revealed that Levenshtein Distance was significantly higher for older adults (mean = 7.59, SD = 2.37) compared to that for younger adults (mean = 5.45, SD = 2.56), t(54) = 3.25, p = .002, Cohen's *d* = 0.87 (95% CI for Cohen's *d*: 1.43, 0.31). Specifically, there was a difference of 2.14 (95% CI: 3.47, 0.82; see Figure 3b).

Discussion

In Experiment 1 we compared landmark memory, associative cue knowledge, and landmark sequence knowledge after a fixed exposure learning phase (three exposures to the route) between younger and older adults. As predicted, (i) younger participants correctly recalled direction changes at more intersections of the route during the learning phase than older participants. Further, the age group x learning trial interaction shows that younger participants' performance increased more than that of older adults between the first and second training trial. This result supports the notion that the learning rate of older adults is reduced compared to that in younger adults. Interestingly, some of the younger participant group reached 100% performance already in the second learning trial (see Figure 2), whilst none of the older adults did.

Under the fixed exposure learning procedure used in this experiment, those (young) participants who learned the route quickly were still required to continue the learning phase. This continued exposure to the route may have led to over-training. That is, since participants had already learned the route before the third learning trial, they may begin acquiring additional information about the route which was not part of their original learning strategy. Since younger adults learned the route quicker in this experiment, they may be particularly prone to over-training which may contribute to inflated age group differences.

Consistent with previous research, there was (ii) no difference between younger and older adults on the Free Landmark Recall Task whereas older adults performed worse than younger adults on tests of both (iii) associative cue knowledge and (iv) landmark sequence knowledge. The Landmark Sequence Task analyses using absolute scoring and Levenshtein Distances both showed an age-related deficit, which suggests that absolute and relative sequence knowledge is impaired in older adults when compared to young adults. This experiment provides a conceptual replication of earlier studies and demonstrates that our environment, learning procedure and tasks used to assess landmark knowledge yielded results which were similar to those reported in earlier studies addressing the effects of cognitive aging on route learning (e.g. Head & Isom, 2010; Wiener et al., 2012).

Experiment 2

Introduction

The aim of Experiment 2 was to investigate age-related differences of landmark knowledge after participants had successfully learned a route. We implemented a flexible exposure learning procedure which allowed participants to learn a route to a performance criterion, before moving on to the test phase. This approach controls for individual differences in learning rate, which the fixed exposure learning procedure used in Experiment 1 did not. Further to this, by ending the learning phase as soon as participants have learned the route, we avoid potentially over-training younger participants, as well as under-training older participants. We were then able to investigate specific age-related differences in the content of route knowledge irrespective of learning rate. In addition, we directly compared the content of route knowledge in this experiment as developed through flexible exposure learning to route knowledge developed through fixed exposure learning by the participants in Experiment 1.

Considering the results of Experiment 1 and previous studies showing impaired route learning ability in aging (Grzeschik et al., 2019; O'Malley et al., 2018), we expected (i) older adults to take significantly more learning trials than younger participants to reach the performance criterion. Since the older adults were not able to navigate the route to a high level by the end of learning in Experiment 1, we expected (ii) older adults to take significantly more than 3 trials to pass the learning phase in this experiment, representing the concern of under-training. Accordingly, if our younger participants were over-trained in Experiment 1, we expected them to take (iii) significantly fewer than 3 trials to pass the learning phase.

Based on the results of the test phase in Experiment 1, we predicted: (iv) no significant difference between older and younger participants in performance on the Free Landmark Recall Task. For the associative cue and landmark sequence tasks, there were several possible permutations of results. Between experiment comparisons may reveal (v) an increase in performance for older adults due to controlling for learning rates (i.e. under-training) and/or a decrease in performance for younger adults due to lack of over-training. Such changes would then result in (vi) reduced or abolished age-effects in one or both of these tasks (O'Malley et al., 2018). Oppositely, it is possible that (vii) age-related differences in the final content of route knowledge persist independently of learning rate, therefore age-related differences on the associative cue and/or landmark sequence task would remain (Allison & Head, 2017).

Method

Participants

Twenty-nine younger participants and 27 older participants were included in the final analysis. An additional six older participants took part in the Experiment but did not reach the performance criteria (90% accuracy) in the learning phase and were excluded from the final analysis. All older participants scored above the MoCA cut off score of 23 (Luis et al., 2009; Waldron-Perrine & Axelrod, 2012). Table 6 summarises the demographic data of the final participant groups.

Table 6 - Participant demographics.

	Sex		Age		MoCA	
		n	Mean	SD	Mean	SD
Younger	Female	15	21.13	4.12		
	Male	14	21.79	4.44		
Older	Female	13	72.08	6.17	26.77	2.20
	Male	14	73.00	6.40	26.43	2.10

Design

The design was as described for Experiment 1 except for a change to the Learning Phase.

Learning Phase

Instead of repeating the route three times during the learning phase, participants navigated the route repeatedly until they recalled at least 90% of the directions correctly (i.e. at least 11 out of the 12 decisions along the route), or until 9 attempts had been made. 9 attempts was chosen as the maximum to ensure that the complete experimental session did not exceed 1.5 hours. Participants moved on to the test phase after they reached the criterion (>90% performance) or after 9 attempts (in which case the test data was excluded from the final analysis).

Procedure

The procedure was the same as described for Experiment 1.

Results

Learning Phase

We analysed the number of learning trials taken to reach the performance criterion which will henceforth be referred to as learning trials. A Welch's two sample t-test revealed that older adults required significantly more learning trials to reach criterion (mean = 5.82, SD = 2.29) compared to younger adults (mean = 4.07, SD = 1.49; see Figure 4), t(44.13) = 3.36, p = .002, Cohen's *d* = 0.91 (95% CI for Cohen's *d*: 1.48, 0.35). Specifically, there was a difference of 1.75 (95% CI: 2.79, 0.70).

In addition, to examine whether age groups were over-trained in Experiment 1, we analysed whether the mean number of trials taken to pass the learning phase was significantly different to 3. A one sample t-test revealed significantly more than 3 trials taken to pass the learning phase for both older adults (mean: 5.82, t(26) = 6.39, p < .001, Cohen's *d* = 1.23, 95% CI for Cohen's *d*: 2.09, 0.37) and younger adults (mean: 4.07, t(28) = 3.87, p < .001, Cohen's *d* = 0.72, 95% CI for Cohen's *d*: 1.50, -0.07).

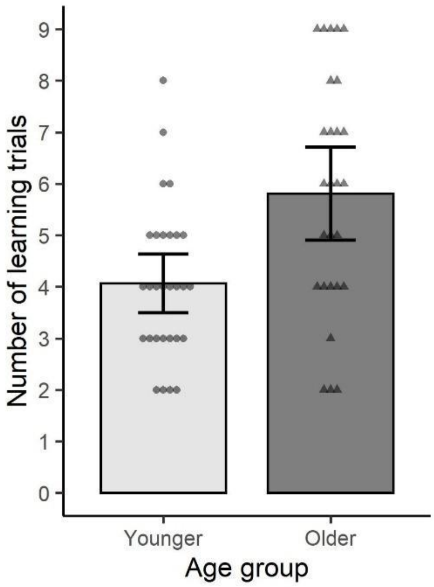

Figure 4 - Number of learning trials taken to reach criterion in the Learning Phase for the younger and older participant groups. Bars are group means, points are individual participants and error bars are 95% confidence intervals.

Test Phase

We conducted three GLMEs[3]; one for each test task. Each model included age group (factor: younger or older; centred using sum contrast coding) as a fixed effect. Since there was variability in the number of learning trials taken for participants to learn the route, we also included learning trials as a

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[3] GLME model as expressed using the lme4 package:
glmer(performance ~ age_group * learning_trials + (1|participant) + (1|stimulus), data = data, family = binomial)

fixed effect (centred around 0). This was to account for the influence of varied amounts of route exposure between participants on test phase performance, similar to Allison and Head (2017) who also took into account performance at learning as a predictor of test performance. The outcome variable for all models was performance which is whether each response given was correct (1) or incorrect (0). Participant and stimulus (landmark) were included as random effects.

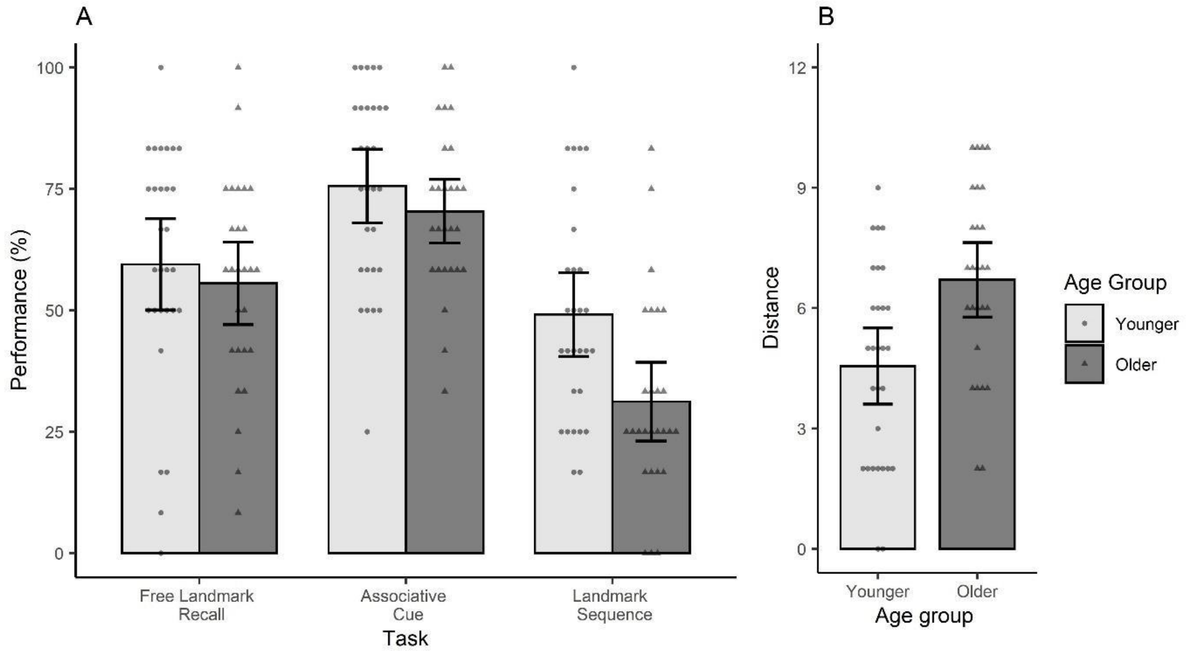

Figure 5 - (A) Average performance in each test task and (B) Levenshtein distances for the Landmark Sequence Task for the younger and older participant groups. Bars are group means, points are individual participants and error bars are 95% confidence intervals.

Free Landmark Recall Task

Estimates, standard errors, z-values, and p-values for the Free Landmark Recall model are reported in Table 7 and show that neither age group nor learning trials were predictors of performance (see Figure 5a). There was no significant interaction.

Table 7 - Coefficients from the Free Landmark Recall Task GLME analysis.

Fixed effect on Free Landmark Recall Task performance	Estimate	Std. error	z-value	p-value
Intercept	0.23	0.20	1.15	.250
Age group (older vs younger)	0.04	0.16	0.22	.826
Learning trials	-0.16	0.17	-0.91	.366
Age group (younger vs older) * learning trials	-0.31	0.17	-1.77	.076

*Significant p values (|p|<0.05)

Associative Cue Task

Estimates, standard errors, z-values, and p-values for the Associative Cue Task model are reported in Table 8 and show that neither age group nor learning trials predicted performance (see Figure 5a). There was no significant interaction.

Table 8 - Coefficients from the Associative Cue Task GLME analysis.

Fixed effect on Associative Cue Task performance	Estimate	Std. error	z-value	p-value
Intercept	1.14	0.21	5.36	<.001*
Age group (older vs younger)	0.22	0.16	1.39	.164
Learning trials	.12	0.17	0.72	.469
Age group (younger vs older) * learning trials	-0.09	0.17	-0.51	.608

*Significant p values (|p|<0.05)

Landmark Sequence Task

Absolute Scoring

Estimates, standard errors, z-values, and p-values for the Landmark Sequence Task model are reported in Table 9 and show that age group was a significant predictor of performance in the Landmark Sequence Task (see Figure 5a). Specifically, younger participants performed better than older participants. Learning trials were not a significant predictor of performance and there was no significant interaction.

Table 9 - Coefficients from the Landmark Sequence Task GLME analysis.

Fixed effect on Landmark Sequence Task performance	Estimate	Std. error	z-value	p-value
Intercept	-0.40	0.15	-2.68	.007*
Age group (older vs younger)	0.44	0.15	2.93	.003*
Learning trials	0.02	0.16	0.13	.900
Age group (younger vs older) * learning trials	0.15	0.16	0.94	.346

*Significant p values (|p|<0.05)

Levenshtein Distance

A Welch's two sample t-test revealed that Levenshtein Distance was significantly higher for older adults (mean = 6.70, SD = 2.35) compared to that for younger adults (mean = 4.55, SD = 2.49), t(53.99) = 3.33, p = <.001, Cohen's *d* = 0.89 (95% CI for Cohen's *d*: 1.45, 0.33). Specifically, there was a difference of 2.15 (95% CI: 3.45, 0.86; see Figure 5b).

Between Experiment Comparison

We also compared performance in the test phase between Experiments 1 and 2. Since participants in Experiment 1 did not learn the route to a performance criterion but instead always completed three learning trials, we could not include number learning trials taken to reach criterion as a fixed effect in this analysis. Each model[4] included age group (factor: younger or older; centred using sum contrast coding) and Experiment (factor: 1 or 2; centred using sum contrast coding) as fixed effects. The outcome variable for all models was performance which is whether each response given was correct (1) or incorrect (0). Participant and stimulus (landmark) were included as random effects.

Free Landmark Recall Task

Estimates, standard errors, z-values, and p-values for the Landmark Recall model are reported in Table 10 and show that there was no difference between Experiment 1 and 2, and there was no significant interaction.

Table 10 - Coefficients from the Free Landmark Recall Task GLME analysis.

Fixed effect on Free Landmark Recall Task performance	Estimate	Std. error	z-value	p-value
Intercept	0.41	0.16	2.51	.012*
Age group (older vs younger)	0.12	0.10	1.25	.211
Experiment (1 vs 2)	-0.06	0.10	-0.58	.562
Age group (younger vs older) * experiment (1 vs 2)	-0.03	0.10	-0.29	.776

*Significant p values (|p|<0.05)

Associative Cue Task

Estimates, standard errors, z-values, and p-values for the Associative Cue Task model are reported in Table 11 and show that both age group and experiment predicted performance. These effects were qualified by the significant age group x experiment interaction. Specifically, the interaction shows that the age effect was reduced between Experiment 1 and 2. This is reflected in the individual experiment analyses in which there was a significant difference between age groups on the Associative Cue task in Experiment 1 and no significant difference in Experiment 2.

Table 11 - Coefficients from the Associative Cue Task GLME analysis.

Fixed effect on Associative Cue Task performance	Estimate	Std. error	z-value	p-value
Intercept	0.92	0.18	5.17	<.001*
Age group (older vs younger)	0.38	0.10	3.72	<.001*

[4] GLME model as expressed using the lme4 package:
glmer(performance ~ age_group * experiment + (1|participant) + (1|stimulus) , data = data, family = binomial)

Experiment (1 vs 2)	0.27	0.10	2.68	<.001*
Age group (younger vs older) * experiment (1 vs 2)	-0.20	0.10	-2.03	.042*

*Significant p values (|p|<0.05)

Landmark Sequence Task

Absolute Scoring

Estimates, standard errors, z-values, and p-values for the Landmark Sequence Task model are reported in Table 12 and show that age group is a significant predictor of performance on the Landmark Sequence Task. There was no difference between Experiment 1 and 2 and no significant interaction.

Table 12 - Coefficients from the Landmark Sequence Task GLME analysis.

Fixed effect on Landmark Sequence Task performance	Estimate	Std. error	z-value	p-value
Intercept	-0.55	0.10	-5.77	<.001*
Age group (older vs younger)	0.48	0.09	5.11	<.001*
Experiment (1 vs 2)	0.08	0.09	0.90	.371
Age group (younger vs older) * experiment (1 vs 2)	-0.05	0.09	-0.56	.575

*Significant p values (|p|<0.05)

Discussion

In Experiment 2 we compared younger and older adults on landmark memory, associative cue knowledge, and landmark sequence knowledge after learning a route to a performance criterion. As expected, we found that (i) older participants took significantly more trials to learn the route than younger participants, demonstrating a reduced route learning rate. The problem of under-training in Experiment 1 was highlighted by older participants in this experiment (ii) taking more than 3 attempts to learn the route. However, we did not find evidence of over-training for the younger participants since they also took more than 3 attempts on average to learn the route.

As in Experiment 1, there was (iv) no difference between younger and older adults on the Free Landmark Recall Task. In contrast to Experiment 1, there was (vi) no difference between age groups on the Associative Cue Task. This change was due to (v) higher performance for the older adults in this experiment compared to Experiment 1 which is in line with our findings of under-training for the learning phase. In contrast, the younger adults in Experiment 1 and 2 showed similar performance on the associative cue task. A different pattern of results was observed for the landmark sequence task, for which older adults in this experiment did not display greater knowledge as compared to those in Experiment 1. Consequently, the age difference remained, indicating that (vii) age-related differences in route knowledge cannot be entirely explained by differences in route learning rate, and that the route knowledge of older adults for a known route lacks sequence information compared to younger adults.

As highlighted in the General Introduction, being able to navigate a route does not mean that the navigator possesses a default route representation, and that is evident in this experiment with the reduced sequence knowledge for older adults compared to younger adults. Given that both groups of participants were able to navigate the route, it is important to consider the consequence of this limitation in the spatial knowledge of older adults. Indeed, whilst our Landmark Sequence Task and the scoring methods we used have been commonly used in previous sequence memory research (Ward et al., 2010), it remains a somewhat abstract measure. That is, it is not clear how well they capture the importance of landmark sequence knowledge for actual navigation and it is therefore not clear what impact age-related declines in landmark sequence knowledge could have for actual navigation. The following experiment will investigate the effect of an age-related landmark sequence knowledge deficit in a navigational context.

Experiment 3

Introduction

We have previously identified an age-related deficit in the acquisition of landmark sequence knowledge for a learned route. The older participants in Experiment 2 were still able to navigate the route successfully, despite having diminished landmark sequence knowledge, and thus the consequence of how an age-related deficit in this type of route knowledge affects navigation behaviour is not clear. The purpose of spatial representations is to allow navigators to resolve a variety of tasks to achieve goal directed wayfinding and avoid disorientation (Wiener et al., 2009). As such, whilst a deficit in sequence knowledge is not particularly harmful to the ability to repeat a route, there are a variety of other situations that sequence knowledge contributes to solving. Intersections and landmarks are tied together during learning (Schinazi & Epstein, 2010) in order to solve such situations should they arise in the future. For example, if landmarks are repeated in the environment, navigators can rely on S-R-S associations to distinguish one landmark from the other (e.g. this post box was preceded by the school whereas the other post box is located after the supermarket) and retrieve the correct motor response (Strickrodt et al., 2015).

Additionally, as familiarity with an environment increases, several known routes may intersect at certain locations. If the navigator has knowledge about the sequence of landmarks along those routes and S-R-S associations, they can integrate those routes into a larger topological representation (Grzeschik et al., 2020). Such representations can then be used to plan routes through the environment to reach different goals, by anticipating the various places that can be travelled to via different movement choices at the present location (Trullier et al., 1997).

Due to the lack of a navigation task which requires the recruitment of sequence knowledge in Experiment 2, it is not entirely clear how the use of the aforementioned processes is affected by aging in a realistic navigation situation. Indeed, although the absolute placement of items was very poor for the older participants (mean: 31.17%), the average Levenshtein Distance for the older adults was 6.7, which is almost half the maximum distance from the correct sequence (maximum = 12). Thus, the older participants clearly maintained some concept of landmark sequence, albeit of lower quality than that of the younger participants. The aim of Experiment 3 was to investigate how this observed deficit in sequence knowledge could affect the ability of older adults to solve navigation tasks with different requirements to those of simple route repetition.

To do this, we developed the Missing Landmark Task in which some landmarks were removed from the route after participants had learnt it to criterion. Participants were required to give route directions at the intersections where landmarks were missing. This task can be solved using landmark sequence knowledge, as participants can use the landmarks which they encountered at the preceding intersection to retrieve what the next landmark in the sequence should be (thus identifying the missing landmark) and recalling the associated direction. This situation presented in the Missing Landmark Task represents the dynamic nature of the real world, in which environmental cues or landmarks used when learning environments may suddenly become unavailable. For example, in residential developments or care environments it is likely that objects such as specific pieces of furniture or paintings that are used by residents as landmarks (O'Malley et al., 2018) will be moved or replaced at some point.

Other than the addition of the Missing Landmark Task, the rest of the experiment was identical to that of Experiment 2. As such, the second aim of Experiment 3 was to test the replicability of the results from Experiment 2. This replication is important, given that the results in Experiment 2 were different from those found in other studies (Allison & Head, 2017; O'Malley et al., 2018), which also vary from each other.

If knowledge about the sequence in which landmarks were encountered is weaker in older adults and this represents impaired use of S-R-S associations, they should become disoriented and unable to complete the Missing Landmark Task. Based on the results of Experiment 2, we predict: (i) Older adults to take significantly more trials to reach the performance criterion during the learning phase than younger participants. (ii) No significant difference between older and younger participants in performance on the Free Landmark Recall Task or the Associative Cue Task. (iii) Older adults to perform significantly worse on the Landmark Sequence Task and the Missing Landmark Task.

Method

Participants

Thirty younger participants and 23 older participants were included in the final analysis. One additional older participant did not reach the performance criterion (90% accuracy) in the learning phase and was excluded from the final analysis. All older participants scored above the MoCA cut off score of 23 (Luis et al., 2009; Waldron-Perrine & Axelrod, 2012). Table 13 summarises the demographic data of the final participant groups.

Table 13 - Participant demographics.

	Sex		Age		MoCA	
		n	Mean	SD	Mean	SD
Younger	Female	15	22.87	3.11		
	Male	15	24.07	4.33		
Older	Female	14	70.07	2.95	27.21	2.08
	Male	9	70.00	5.39	27.22	1.99

Design

The design was identical to the one described in Experiment 2, with the addition of the Missing Landmark Task to the test phase.

The Missing Landmark Task

In the Missing Landmark Task, participants were placed in a corridor along the route and were passively navigated past the next intersection with landmarks present. At the following intersection the landmarks were removed (see Figure 6) and the video was paused. The participants were required to indicate the direction of travel to continue along the route. As soon as participants responded they began the next trial, thus they did not receive feedback. There were 11 trials in total – one less than the number of intersections in the route since the last intersection has no following intersection. The trials were presented in a randomized order.

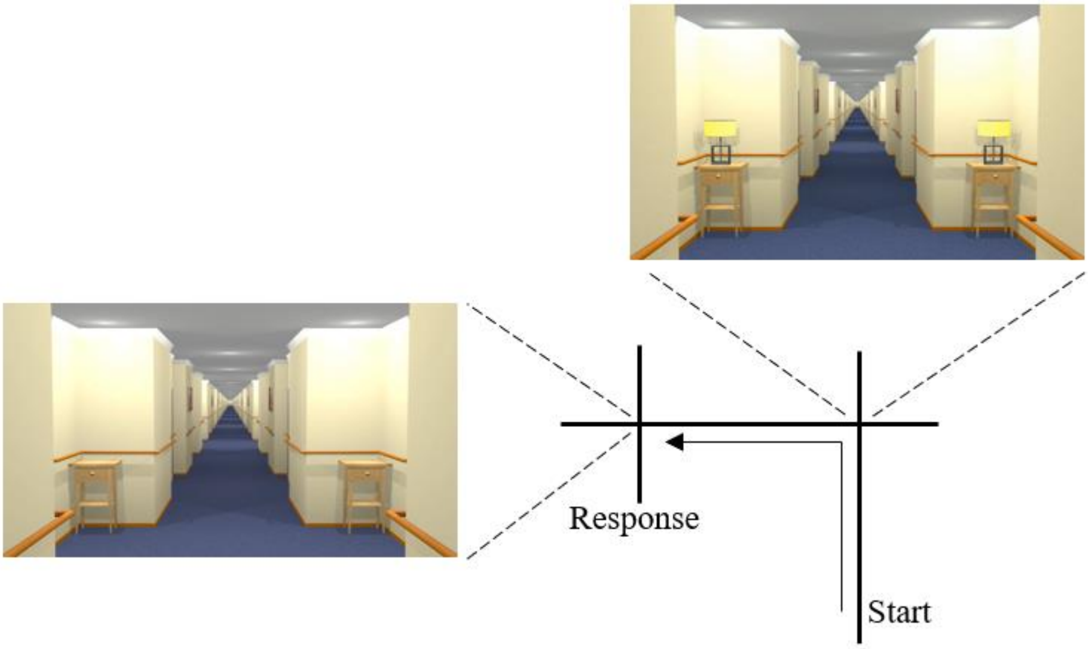

Figure 6 - Example Missing Landmark Task trial. Participants were passively navigated from a random start location along the route past an intersection with the landmark in place, to the following intersection where the landmark is missing. Here the video pauses and participants are required to indicate which direction continues along the route.

Procedure

The procedure was as described in Experiments 1 and 2 with the addition of the Missing Landmark Task. The Missing Landmark task was always conducted before the Landmark Sequence Task. This was done to avoid the sequence of landmarks participants created in the Landmark Sequence Task interfering with the Missing Landmark Task.

Results

Learning Phase

We analysed the number of learning trials taken to reach the performance criterion. As in Experiment 2, a Welch's two sample t-test revealed that the number of learning trials was significantly higher for older adults (mean = 4.61, SD = 2.50) than for than younger adults (mean = 3.37, SD = 1.54; see Figure 7), t(34.48) = 2.10, p = .04, Cohen's *d* = 0.62 (95% CI for Cohen's *d*: 1.19, 0.05). Specifically, there was a difference of 1.25 (95% CI: 2.44, 0.04).

To examine whether young participants were over-trained in Experiment 1, we analysed whether the mean number of trials taken to pass the learning phase was significantly different to 3 (the number of learning trials in Experiment 1). A one sample t-test revealed significantly more than 3 trials taken to pass the learning phase for older adults (mean: 4.61, t(22) = 3.09, p = .005, Cohen's *d* = 0.64, 95% CI for Cohen's *d*: 1.53, -0.24). There was no significant deviation from 3 trials for younger adults (mean: 3.37, t(29) = 1.30, p < .203, Cohen's *d* = 0.24, 95% CI for Cohen's *d*: 0.99, -0.51).

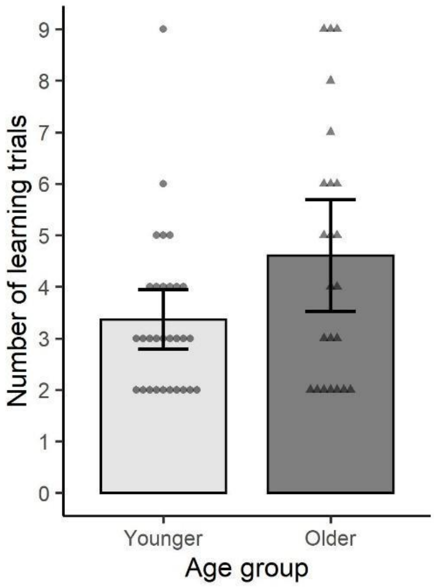

Figure 7 - Number of learning trials taken to reach criterion in the Learning Phase for the younger and older participant groups. Bars are group means, points are individual participants and error bars are 95% confidence intervals.

Test Phase

We conducted four GLMEs[5]; one for each test phase. Each model included age group (factor: younger or older; centred using sum contrast coding) and number of learning trials (centred around 0) as fixed

[5] GLME model as expressed using the lme4 package:
glmer(performance ~ age_group * learning_trials + (1|participant) + (1|stimulus), data = data, family = binomial)

effects. The outcome variable for all models was performance which is whether each response given was correct (1) or incorrect (0). Participant and stimulus (landmark) were included as random effects.

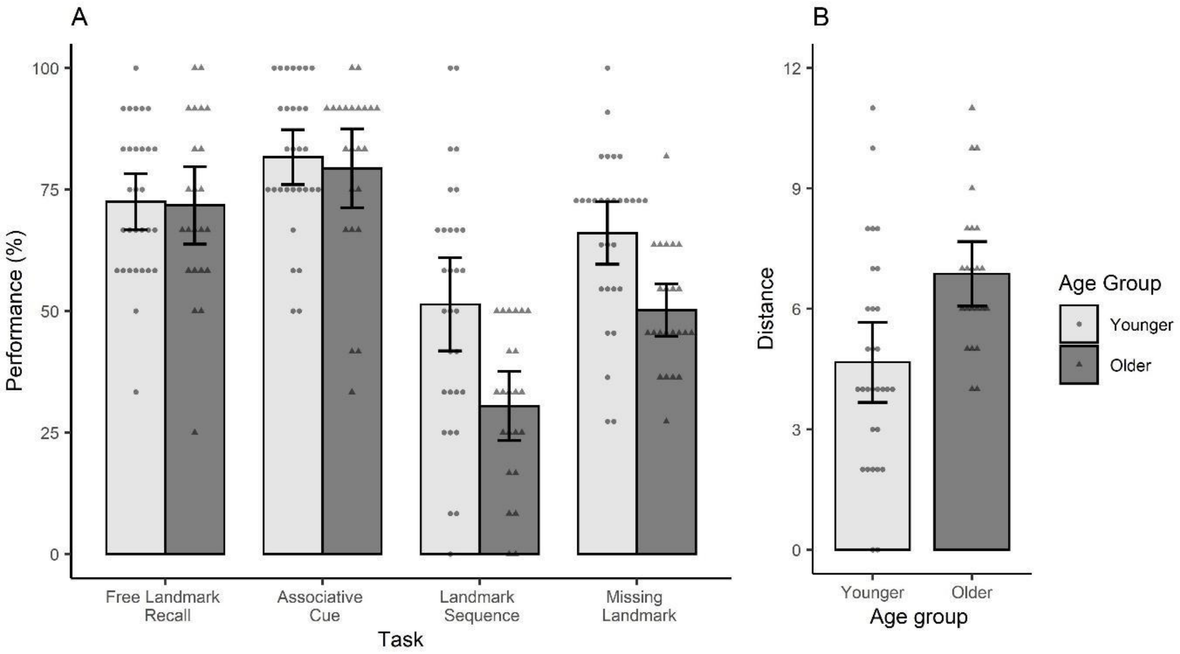

Figure 8 - (A) Average performance in each test task and (B) Levenshtein distances for the Landmark Sequence Task for the younger and older participant groups. Bars are group means, points are individual participants and error bars are 95% confidence intervals.

Free Landmark Recall Task

Estimates, standard errors, z-values, and p-values for the Free Landmark Recall model are reported in Table 14. As in Experiment 2, neither age group nor learning trials predicted performance (see Figure 8a) and there was no significant interaction.

Table 14 - Coefficients from the Free Landmark Recall Task GLME analysis.

Fixed effect on Free Landmark Recall Task performance	Estimate	Std. error	z-value	p-value
Intercept	1.05	0.17	6.21	<.001*
Age group (older vs younger)	-0.01	0.13	-0.08	.936
Learning trials	-0.09	0.14	-0.64	.525
Age group (younger vs older) * learning trials	0.01	0.14	0.04	.967

*Significant p values (|p|<0.05)

Associative Cue Task

Estimates, standard errors, z-values, and p-values for the Associative Cue Task model[6] are reported in Table 15. As in Experiment 2, neither age group nor learning trials predicted performance (see Figure 8a) and there was no significant interaction.

Table 15 - Coefficients from the Associative Cue Task GLME analysis.

Fixed effect on Associative Cue Task performance	Estimate	Std. error	z-value	p-value
Intercept	1.61	0.17	9.72	<.001
Age group (older vs younger)	0.08	0.16	0.46	.649
Learning trials	<0.01	0.16	0.03	.980

*Significant p values (|p|<0.05)

Landmark Sequence Task

Absolute Scoring

Estimates, standard errors, z-values, and p-values for the Landmark Sequence Task model are reported in Table 16. As in Experiment 2, age group was a significant predictor of performance in the Landmark Sequence Task (see Figure 8a). Specifically, younger participants performed better than older participants. There was no main effect of learning trials. There was a significant age group (younger vs older) x learning trials interaction which shows that the size of the age group effect decreases as number of learning trials increases.

Table 16 - Coefficients from the Landmark Sequence Task GLME analysis.

Fixed effect on Landmark Sequence Task performance	Estimate	Std. error	z-value	p-value
Intercept	-0.54	0.16	-3.37	<.001*
Age group (older vs younger)	0.46	0.15	3.01	.003*
Learning trials	-0.16	0.16	-1.00	.316
Age group (younger vs older) * learning trials	-0.34	0.16	-2.10	.036*

*Significant p values (|p|<0.05)

[6] This model's fixed effects structure deviates from that of the other models in that the intercept only model would not converge with the fixed effect interaction of age group and learning trials. The model with the interaction would converge with the addition of a random by stimuli slope for learning trials. This model was not selected using our stated GLME procedure, but the fixed effects did not differ from the reported model and the interaction was non-significant.

Levenshtein Distance

A Welch's two sample t-test revealed that Levenshtein Distance was significantly higher for older adults (mean = 6.87, SD = 1.87) compared to that for younger adults (mean = 4.67, SD = 2.67), $t(50.63) = 3.53$, $p < .001$, Cohen's $d = 0.94$ (95% CI for Cohen's d: 1.52, 0.35). Specifically, there was a difference in Levenshtein Distance of 2.20 (95% CI: 3.46, 0.95; Figure 8b).

Missing Landmark Task

Estimates, standard errors, z-values, and p-values for the Missing Landmark Task are reported in Table 17 and show that age group was a significant predictor of performance on the Missing Landmark Task (see Figure 8). Specifically, younger participants performed better than older participants. There was no effect of learning trials and no significant interaction.

Table 17 - Coefficients from the Missing Landmark Task GLME analysis.

Fixed effect on Landmark Sequence Task performance	Estimate	Std. error	z-value	p-value
Intercept	0.33	0.10	3.47	<.001*
Age group (older vs younger)	0.31	0.09	3.35	<.001*
Learning trials	-0.08	0.10	-0.79	.430
Age group (younger vs older) * learning trials	-0.03	0.10	-0.32	.748

*Significant p values (|p|<0.05)

Since both the Landmark Sequence Task and the Missing Landmark Task are intended to measure the extent to which people know the sequence in which landmarks were encountered, we also analysed their relationship. There was a significant correlation between performance on the Landmark Sequence Task and the Missing Landmark Task (see Figure 9), $r = 0.59$, $t(51) = 5.21$, $p < .001$.

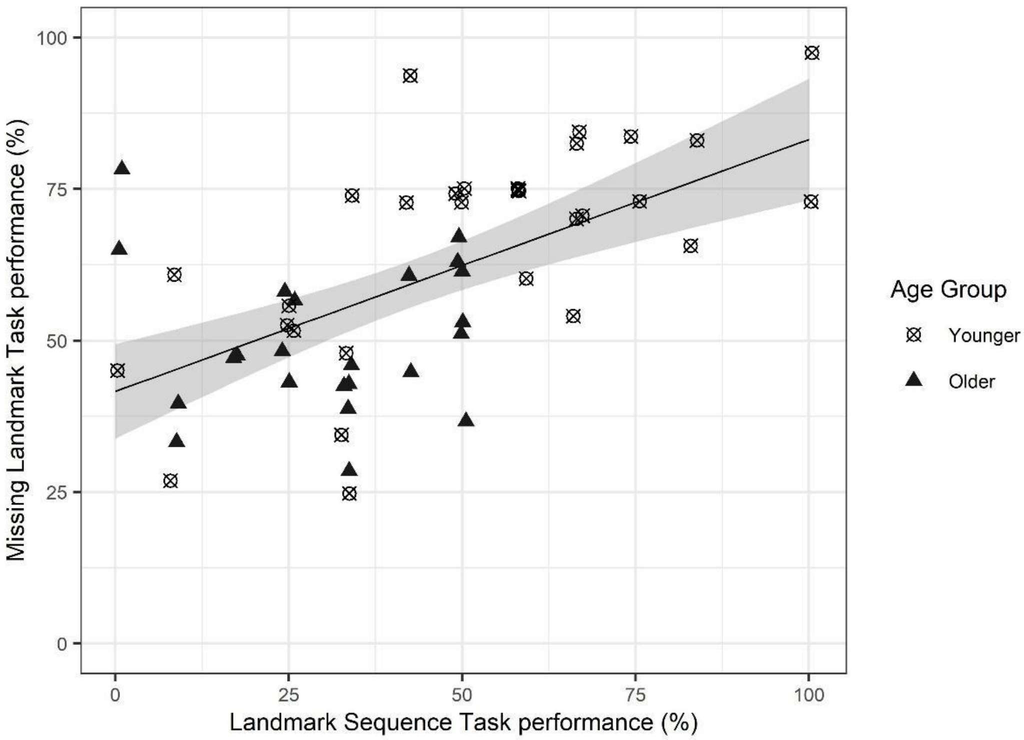

Figure 9 - Performance on the Landmark Sequence Task and the Missing Landmark Task for the older and younger participant groups. Data points are jittered for visibility and regression slope shows 95% confidence interval.

Discussion

Experiment 3 was a replication of Experiment 2 with the addition of the newly developed Missing Landmark Task. We replicated the results of Experiment 2, showing (i) that older adults took longer to learn the route, (ii) that they performed worse on the Landmark Sequence Task, and (iii) that performance in the Free Landmark Recall Task and the Associative Cue Task was similar between age groups. Finally, in the new Missing Landmark Task our older participants performed worse than our younger participants.

We developed the Missing Landmark task as a navigational test for landmark sequence knowledge. Impaired performance on the Missing Landmark Task demonstrates that older adults are more likely to become disoriented when landmark information is disrupted (in this case removed). We believe that this is a result of older adults forming weaker S-R-S associations during route learning. The correlation between the Missing Landmark Task and the Landmark Sequence Task provides evidence for the validity of the Landmark Sequence Task in assessing landmark sequence knowledge that is relevant for navigation.

Additionally, in this study the number of learning trials was not a predictor for any of the test tasks, as in Experiment 2. However, we found a sole interaction between the number of learning trials taken to reach criterion and age group on Landmark Sequence Task performance in this experiment. This interaction was not present in Experiment 2 and not found in the analysis for any of the other tasks across all experiments. Given that the age group x learning trials interaction appears unreliable and was only found in one model, we are cautious that it may be a false positive and therefore do not attribute much meaning to this finding.

General discussion

We conducted three experiments to investigate age related differences in the acquisition of route landmark knowledge after learning a route through either a fixed exposure or a flexible exposure learning procedure. Experiment 1 used a fixed exposure learning procedure in which participants navigated a route three times before being tested on their landmark knowledge. In Experiment 1 we replicated previous findings showing age-related differences in associative cue and landmark sequence knowledge (c.f. Head & Isom, 2010) but no difference between age groups on the ability to freely recall landmarks (c.f. Cushman et al., 2008). Experiment 2 used a flexible exposure learning procedure in which participants repeatedly navigated the route until they reached a 90% performance criterion. The results showed that older adults took more attempts to reach criterion than younger adults (c.f. Grzeschik et al., 2019; O'Malley et al., 2018). In contrast to Experiment 1, however, there was no difference between older and younger participants on the Associative Cue Task (c.f. O'Malley et al., 2018) while the age group difference on the Landmark Sequence Task remained (c.f. Allison & Head, 2017). Experiment 3 again used the flexible exposure learning procedure and replicated the findings from Experiment 2. In addition, participants performed the Missing Landmark Task which was designed to investigate the use of landmark sequence knowledge in a navigation context, in which older participants performed worse than younger participants.

As expected, older adults showed route learning deficits in all experiments. Specifically, in Experiment 1, older participants made more errors when navigating the route during learning (c.f. Barrash, 1994; Hartmeyer et al., 2017), showing that younger participants had learnt more about the route at the point they entered the test phase. In Experiments 2 and 3, older participants took more learning trials to reach the performance criterion (c.f. Grzeschik et al., 2019; O'Malley et al., 2018). Essentially, when given a limited amount of time to learn a route, older adults were less able to repeat the route than younger adults. However, when given the extra time/exposure that older adults required, they could learn and navigate a route to the same level as younger adults. We included number of learning trials as a predictor in our models for test phase performance. Number of exposures taken to pass learning had no predictive value on test phase performance across the experiments. This is important, since it indicates that participants who took longer to learn the route were not at an advantage in the test phase despite having had more exposure to the route than participants who completed the learning phase in fewer trials.

Greater time to learn the route in our study indicates that older adults take more time to acquire the knowledge required to repeat the route. Improved associative cue knowledge for the older adults in Experiment 2 compared to Experiment 1 suggests that they are relying on S-R learning, at least in part, to navigate successfully (Trullier et al., 1997; Waller & Lippa, 2007). This result is in line with the suggestion that reduced ability to navigate the route by the end of the learning phase under fixed exposure conditions are a result of age-related impairments in associative learning (Naveh-Benjamin, 2000; Zhong & Moffat, 2016). Indeed, our older participants showed the associative cue deficit with only three exposures to the route, and in the flexible exposure conditions they, on average, took more than three exposures to complete learning. Taken together, these findings demonstrate that under the fixed exposure learning conditions, older adults are under-trained when compared to the younger participants on the content of their route knowledge.

Under the flexible exposure learning condition, the associative cue knowledge of the older adults in our study improved to the same levels as that of the younger adults, which is consistent with Grzeschik et al. (2019) and O'Malley et al. (2018), but conflicts with results by Allison and Head (2017). Whilst the studies by Grzeschik et al. (2019) and O'Malley et al. (2018) used very short routes with four intersections, our study demonstrates that older adults are able to learn and use S-R associations to navigate longer routes (at least up to 12 intersections). In the study by Allison and Head (2017) the older adults performed at ~71% in the associative cue test, which is not dissimilar to our older adults in Experiment 2 (70.37%). The younger adults in their study, however, performed significantly higher (at ~86%) and numerically higher than our younger adults in Experiment 2 (75.57%). Since the learning procedure used by Allison and Head (2017) required participants to complete a minimum number of learning sessions even if they already could navigate the route, it is possible that their younger adults were over-trained, resulting in inflated associative cue performance. Our younger adults in Experiment 2, in contrast, were not over-trained as the learning phase was terminated as soon as they reached the performance criterion, similar to the procedures by Grzeschik et al. (2019) and O'Malley et al. (2018). This explanation could account for the conflict between our study and Allison and Head (2017) regarding the presence of age-related differences on the associative cue task.

Our findings suggest that older adults were able to overcome the deficit in associating landmarks and directions if they are given enough time in the learning phase. It is possible that cognitive resource limitations experienced by older adults (Craik & Byrd, 1982; Denise C. Park & Festini, 2017) contributes to the associative learning deficit usually observed under fixed learning conditions (Craik, 2012; Naveh-Benjamin & Kilb, 2014). With our flexible learning procedure, the older navigators were able to compensate for declining resources through longer learning times to acquire the S-R associations. This explanation is further supported by the between experiment interaction showing that the older adult age group particularly benefited from the change in learning procedure with regards to associative cue performance. Indeed, the Associative Cue Task performance of younger adults was nearly identical in Experiments 1 and 2 despite the differences in learning procedure. Overcoming the associative learning deficit through additional exposure could be due to attentional depletion or attentional prioritisation (Naveh-Benjamin & Kilb, 2014).

Attentional depletion refers to the notion that cognitive resources are divided between multiple, concurrent learning streams such as the encoding of items and the binding of information to those items. For older adults, the to-be-divided resources are more limited compared to younger adults and thus the quantity and quality of encoding is reduced (Craik, 2012; Craik et al., 2010). Overcoming attentional depletion with additional learning time would involve a gradual increase in all the different types of knowledge being acquired (Naveh-Benjamin et al., 2004). Such concurrent and integrated acquisition of spatial knowledge has been demonstrated for younger adults (Ishikawa & Montello, 2006; Montello, 1998; Schinazi & Epstein, 2010). However, this was not the case for our older adults, for whom we observed a large increase in associative cue knowledge between Experiments 1 and 2, with no changes in landmark memory or sequence knowledge. Therefore, attentional depletion does not account for the pattern of results observed in this study.

Instead, our findings are more in line with attentional prioritisation, which suggests that cognitive resources are directed towards the different components of the task one after the other, in order of priority. For route learning, Zhong and Moffat (2016) suggested that older adults first prioritise the learning of landmark identities, whilst neglecting to bind directional information to those landmarks. This pattern is also evident in our study where older adults showed good knowledge for landmark identities which was already formed during the three learning trials provided in Experiment 1, but they showed relatively poor associative cue knowledge. During the additional learning trials in Experiments 2 and 3, older participants have then been able to direct their resources towards the learning of S-R associations to overcome this deficit. We believe this explanation is plausible given that dual task paradigms have shown that modulation of attentional engagement during route learning is not only preserved for older adults, but they show engagement of a greater proportion of their attention at intersections where they had to associate landmarks with directional information compared to younger adults (Hartmeyer et al., 2017; Hilton et al., 2019). Learning landmark identities before learning associative information is also in line with frameworks of spatial knowledge acquisition which state that landmarks are learned first and before associative cue or sequence knowledge is acquired (Chrastil, 2013; Foo et al., 2007; Siegel & White, 1975). Indeed, parahippocampal representations of landmarks have been shown to form after only a single exposure in younger adults (Janzen et al., 2007).

Not all aspects of route knowledge were equated across age groups in our study, however. Under the flexible learning procedures used in Experiments 2 and 3, we still observed age-related deficits in landmark sequence knowledge. This is in contrast to findings of O'Malley et al. (2018), who did not report differences between age groups. Their participants, however, were aware of the up-coming tests and therefore could amend their learning strategy to acquire such knowledge (Naveh-Benjamin et al., 2007), which is plausible considering they used only 4 landmarks. Indeed, the younger participants in their study also performed (82.81%) much better than our younger participants (47.99% - 51.39%).

Following the attentional prioritisation explanation, the results of the landmark sequence task indicate that older adults prioritised the learning of associative cue knowledge over sequence learning, once the initial encoding of landmark identities was completed. This order is intuitive, since recalling cued directions alone would be enough to repeat the route in our environment (as long as landmarks are unique and not repeated along the route, see Strickrodt et al., 2015). Importantly, this finding demonstrates that even when older navigators have learned a route successfully, the overall content of their route knowledge is impoverished compared to the richer representation held by younger navigators. Attentional prioritisation seems to allow older navigators to acquire the essential knowledge to successfully complete the basic task in the learning session, which is repeating the exact same route (Wiener et al., 2012). However, the cost of such a strategy is reduced learning of wider information about the environment.

Although sequence knowledge was not required to repeat the route during the learning phase, we still expected navigators to acquire some knowledge about the order of landmarks. This is in line with more general sequence learning studies, which show that even in the absence of explicit instruction or requirement to learn a sequence, repeated exposures are still associated with sequence learning (Oberauer & Meyer, 2009). The incidental acquisition of sequence information has also been shown to be impaired in older adults which, in line with our interpretation, is suggested to be due to differences in cognitive capacity between age groups (Vandenbossche et al., 2014). For route navigation the learning of landmark sequence knowledge may not be vital for the repeating of a route, but it would enable behaviours such as response priming (Schinazi & Epstein, 2010; Schweizer et al., 1998) and error monitoring. We did not analyse such measures in our study so although we find that older adults can repeat a route without well-formed sequence knowledge, it is possible that younger adults would have these other advantages over older adults at the point of successful navigation.

Note that, environments in the real world are dynamic and ever changing and that beside route repetition, there are several other navigation tasks that humans solve in daily life (Wiener et al., 2009). Rich representations of environments support flexibility in navigation behaviour by affording the use of different navigation strategies and the solution of different tasks and therefore also help to deal with environmental changes. We introduced the missing landmark task in Experiment 3, which involved navigating past an intersection to the following intersection, at which point the participants were required to decide which direction the route continued in. The latter intersection had the landmark removed, requiring participants to use information about the preceding intersection to solve the task. We found that older adults performed worse on this task than younger adults. This deficit cannot be explained by either lack of familiarity with the route, since all participants underwent flexible exposure learning, or by poor landmark memory or by poor associative cue knowledge since age groups performed similarly in those tests. Instead the impaired performance of older adults can be explained by the lack of sequence knowledge, as supported by the significant correlation between sequence task and missing landmark task performance.

The missing landmark task results highlight that even when older adults are able to navigate a familiar route, the flexibility in their navigation behaviour is reduced by their limited route knowledge. For locations frequented by an older population, such as hospitals, shopping centres or care facilities, it is important to understand that altering features may significantly affect the navigability for older adults, even if they seem familiar with the environment. A question for future research is whether older adults would be able to overcome the sequence knowledge deficit in the same way as they overcame the associative cue deficit in our study. Our explanation of attentional prioritisation would suggest that this might be achieved through changing the relevance of sequence knowledge during learning (as in O'Malley et al., 2018), or possibly via extra learning trials after successful navigation is achieved. Alternatively, it is possible that older adults would continue to struggle to intentionally acquire landmark sequence knowledge, as shown by more general sequence learning paradigms (Golomb et al., 2008; Kahana et al., 2002).

The findings of this study support Vakil and Agmon-Ashkenazi (1997) suggestion that age-related differences in learning rate of information should be considered alongside differences in baseline performance. In our study, performance after the fixed learning procedure can be considered the baseline, where immediate age-related deficits emerge in the learning of specific information. We then demonstrate that accounting for learning rate reveals dissociated development of these baseline differences. Specifically, our older adults eventually learned the associative cue information to the same performance levels as younger adults, whilst their landmark sequence knowledge still showed age-related deficits. The flexible exposure learning procedure examined in this study may be a means by which learning research in other domains can account for age-related differences in learning-rates.

In summary, this study has replicated existing findings that under fixed exposure route learning conditions, older adults have preserved memory for landmarks but worse associative cue and sequence knowledge compared to younger adults. We then demonstrate that under a flexible exposure learning procedure, the associative cue deficit is attenuated, whilst the sequence knowledge deficit remains. We suggest that such a pattern of findings is a result of older adults prioritising their limited cognitive resources to learn in a piecemeal manner, compared to the quicker and more simultaneous learning conducted by younger participants. Attentional prioritisation leads older adults to first encode landmark identities without the association of directional information, and then to later acquire directional information that is not linked to the adjacent locations. Importantly, the cost of such a strategy is reduced flexibility in the final route representation, namely a lack of sequence knowledge even after successful navigation is achieved, which results in increased likelihood of disorientation when faced with other navigation tasks along the same route.

Additional Information

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