Older Adults Show Less Flexible Spatial Cue Use When Navigating in a Virtual Reality Environment Compared With Younger Adults

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ABSTRACT: Daily life requires accurate navigation, and thus better understanding of aging on navigational abilities is critical. Importantly, the use of spatial properties by older and younger adults remains unclear. During this study, younger and older human adults were presented with a virtual environment in which they had to navigate a series of hallways. The hallways provided 2 general types of spatial information: geometric, which included distance and directional turns along a learned route, and featural, which included landmarks situated along the route. To investigate how participants used these different cue types, geometric and/or landmark information was manipulated during testing trials. Data from 40 younger (20 women) and 40 older (20 women) adults were analyzed. Our findings suggest that (1) both younger and older adults relied mostly on landmarks to find their way, and (2) younger adults were better able to adapt to spatial changes to the environment compared with older adults.

KEYWORDS: Spatial cognition, geometry, landmarks, aging, navigation, virtual reality

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Introduction

Navigation requires that one first establish an accurate sense of heading. During visually guided orientation, research has shown that navigators encode both geometric and featural cues.[1] The former includes direction and distance information (eg, the length of a wall), whereas the latter includes non-metric information (eg, the specific color pattern of a wall). Featural cues also include specific aspects of landmarks, whether they are proximal to a location or more distal. Landmarks that are close to a location can act as a beacon for that location in which case spatial learning is quite simple; landmarks that are more distal pose a more complex challenge in that their spatial arrangement relative to a location must be remembered to be effective. Although much research has been conducted into how these cues are used to navigate, less is known about how the use of these cues changes with advanced age.

To investigate how both geometric and featural properties can be used by a subject to find their way within a space, a reorientation paradigm is commonly employed as it can easily segregate these 2 cue types using a simple environment.[2-5] During reorientation studies, a subject learns to locate a hidden target in 1 corner of a walled space when both geometric and featural cues are available during a learning phase and again searches for the hidden target after the cues are manipulated or removed during a testing phase.[5] Where subjects choose to search during these test trials can reveal which spatial cues they relied on most when initially learning about the environment. During test trials, in which geometry and features provide conflicting information, participants have to choose which type of cue they find more reliable.[3] Results from these studies show that people readily encode both geometric and featural cues,[2,4,5] with greater reliance on geometry in smaller environments and features in larger environments.[3] However, because the participants in many of these studies have been either young children or otherwise healthy younger adults,[6] comparatively less is known about the effect that advanced age has on such encoding.

Previous research has shown that advanced age can affect navigational ability in different ways.[7-11] For example, when spatial knowledge was examined by measuring the duration and distance traveled during a complex-maze route-learning task, results showed more deviations from the correct route by older (65+ years) adults compared with younger adults (<45 years).[8] Similar findings were reported using a computerized version of the *Morris Water Maze* task whereby older participants (mean age: 73.7 years) spent less total time and devoted a smaller proportion of the path length traveled, inside the correct quadrant, compared with younger adults (mean age: 28.6 years).[9] In another study,[10] younger (mean age: 21.8 years) participants were more able to employ a novel shortcut through a virtual reality (VR) city environment than older (mean age: 68.7 years) participants. It should be noted that the use of a novel shortcut is considered to be the hallmark measure of a complex mental allocentric map complete with landmarks.[11] Generally speaking, older adults tend to be less efficient during navigation tasks than their younger counterparts, a difference that can often be traced to older adults being less effective at integrating distal landmarks into a stable spatial framework when learning new environments.[7,12-22]

Studies of spatial cognition have used both real environments[2,3,14-16] as well as VR environments,[4,5,7-10,12,13,17,19,21,22] with VR paradigms having the advantage of easily tracking and recording responses such as trajectories taken during trials and time to complete trials. A general assumption of VR paradigms is that spatial decision-making in a virtual world is largely transferrable to the real world,[23-25] and their main strength is that they allow researchers to manipulate key elements of the environment such as altering room dimensions, changing start location of trials, or removing/relocating landmarks. More immersive VR designs, such as those using head-mounted displays (HMDs) to display the environment to participants, have the added advantage of providing a more realistic navigational experience. The drawback of these designs, however, is that they can be prone to inducing motion-related fatigue which can affect stress levels and ultimately decision-making.[26-29] Research has generally shown that spatial cognition performance using these kinds of fully immersive paradigms does not differ substantially from that using paradigms employing more traditional desktop or laptop computer displays.[29-31]

For this study, we employed a paradigm that allowed participants to navigate within a VR environment (hallway complex) displayed to them via an HMD with movement provided by a custom-designed wheelchair, called a VRNChair, which provided both proprioceptive and vestibular inputs to participants.[32] For those participants who experienced motion-related fatigue during initial training with the HMD, a switch from the HMD to a comparable laptop display was made, which provided us an opportunity to compare performance using both types of displays. Our specific goal was to examine whether the encoding of geometry and features differs between younger (mean age: 26.2 years) and older (mean age: 67.6 years) participants. Specifically, when an environment is manipulated (ie, by changing the geometry or removing some or all of the landmarks), do younger and older adults use different strategies when searching for a desired destination?

Method

Participants

A total of 51 older adults (28 women; mean age: 67.6 ± 9.1 years) and 50 younger adults (28 women; mean age: 26.2 ± 4.4 years) participated in this study; of that total, 21 participants either reported motion-related fatigue or failed to meet training criteria (see section "Procedure"), resulting in data from 80 participants being used in the final analyses. Older adults were recruited from a known participant pool of older healthy adults who had previously participated in an earlier unrelated VR study.[33] Prior to the start of the experiment, cognitive abilities were tested using the Montreal Cognitive Assessment (MoCA),[34] which confirmed that all older participants met the standard for normal cognitive functioning. All younger adults were student volunteers recruited from the campus of the University of Manitoba. All participants signed a consent form approved by the Biomedical Research Ethics Board of University of Manitoba.

VR components and materials

To investigate how participants navigated during the task, we designed a virtual hallway environment using Blender 2.74, which participants could view on either an Oculus DK2 HMD or a laptop display (see section "Procedure"). To move within the environment, a custom-designed wheelchair, called the VRNChair,[31] allowed the translation of real-world movement via the wheelchair to virtual movement within the VR environment.

The hallways each measured 27 × 32 × 2.44 virtual units (vu) (width × length × height) wherein 1 vu corresponded to approximately 1 m in the real world. We used Unity 5.1.3f[35] to design a custom game engine that integrated the hallway models, VRNChair, the HMD (Oculus Rift DK2), and the logging system to record each participant's motion during trials. The HMD resolution was 1920 × 1080 with a total field of view of 106 degrees. As there were some participants who experienced discomfort while wearing the HMD, for these individuals we replaced the HMD with a 17-in laptop display (resolution 1920 × 1080) while preserving the same field of view as the HMD. The experimental computer was equipped with an NVIDIA GeForce GTX 980m graphic card to draw the virtual environment on either the HMD or the monitor in real time without dropping frames.

Virtual environment

The environment contained 5 hallways organized as grids running east-west (E-W) and north-south (N-S) with each hallway being 2 vu wide. The area surrounded by each hallway is referred as 1 "block," with each block measuring 3 vu in an E-W direction and 4 vu in an N-S direction, as depicted in a top-down view in Figure 1. The north and south sides of the walls (except for the boundary of the environment) contained an identical orange door in the middle, each measuring 0.91 × 2.44 vu (width × height).

Procedure

The HMD was calibrated for each participant by measuring their interpupillary distance using a tool provided by the manufacture (ie, Oculus VR, LLC). Next, the researcher instructed the participant to "find the correct door" in the virtual environment. To choose a door, the participant had to move close enough to it and click a button attached to their index finger. During training trials, participants could follow an onscreen arrow that would lead them toward the correct door.

The experiment proceeded in a set order for all participants (see Figure 2): First, 2 training trials were followed by 1 control trial, then 2 additional training trials followed by a second

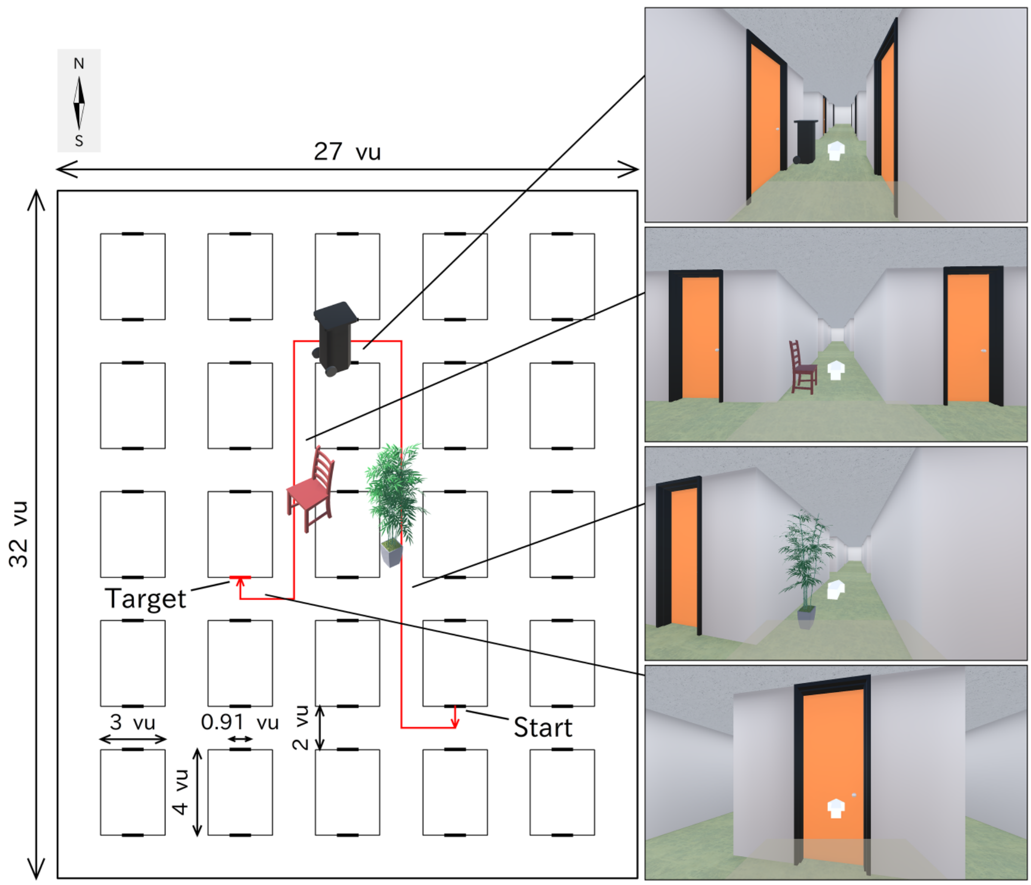

Figure 1. Left panel: A schematic top-down view of the training environment. The red line represents the predetermined route for all training trials. Along the route, there were 3 landmarks in the following order: a tree, a garbage bin, and a chair. Right panel: Screenshots of the virtual environment from several viewpoints. The white arrow in the middle of the screen guided the participants toward the target door.

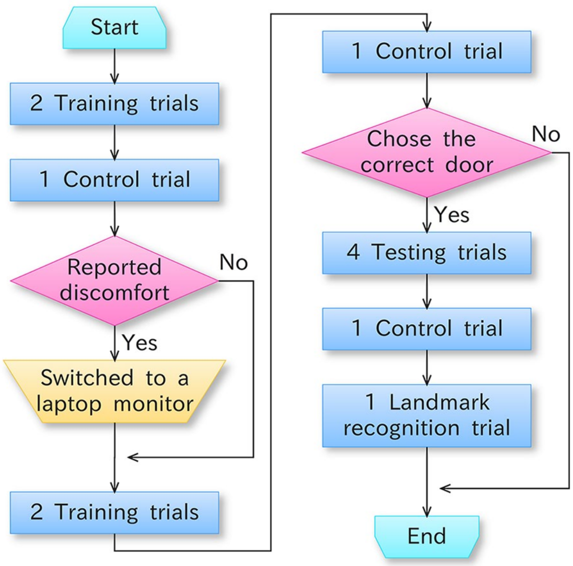

Figure 2. Methodological flowchart of the experiment.

control trial, followed by a block of 4 testing trials (counterbalanced across participants), followed by a third control trial, and finally a Landmark Recognition trial. During the first trial, all participants used the HMD; for those participants who reported motion-induced fatigue prior to completion of the first control trial (the third trial in total), the HMD was replaced with a laptop display placed in front of them on the VRNChair and they were allowed to continue the experiment (see Figure 3 for a picture of both the HMD and laptop viewing conditions). For those participants who continued to report discomfort or dizziness following the fourth trial, the experiment was terminated and the data were not used. To limit the possibility of motion-related fatigue with the HMD, participants removed the HMD between trials. Altogether, the experiment took up to 60 minutes to complete.

Training and control trials

Participants started each trial from a consistent start location. Participants began with a learning phase consisting of training trials in which they could navigate the environment and learn the location of the correct door. During training trials, a white arrow guided the participant toward a target door along a predetermined route. Along the route, the participant passed 3 landmarks in the same order: a plant, a garbage bin, and a chair. When the participant missed one of the turns to follow the route, or made an incorrect turn, the onscreen arrow pointed

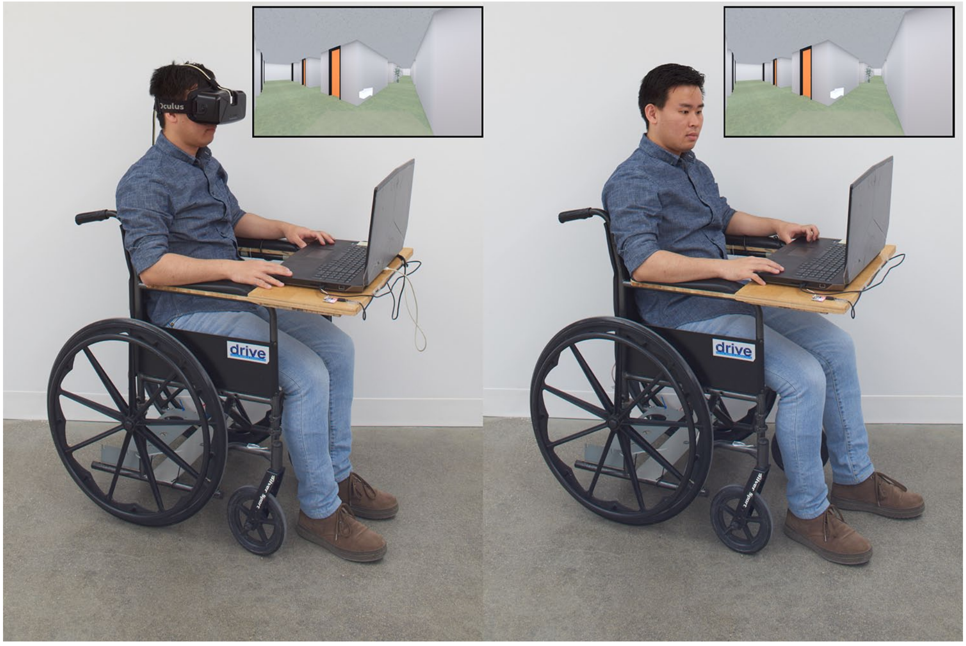

Figure 3. Two experimental setups: using a head-mounted display (left) and a laptop screen (right). The insets depict an example of the virtual environment that the participants observed.

them back onto the route. When the participant chose the correct door, the computer provided positive feedback with a verbal "good job" message and the trial ended.

Once participants had experienced 2 training trials, they were presented with a control trial; this block of 2 training trials/1 control trial was repeated twice (for a total of 6 trials). During control trials, the environment was identical to that during training trials, except that the white arrow was no longer visible and no verbal feedback was provided following a choice. Participants who chose the correct door at the end of the second control trial advanced to testing; if the participant chose an incorrect door, the experiment was terminated.

Testing trials

Each testing trial contained a different manipulation that allowed us to investigate the spatial properties that participants had encoded during training. Specifically, we examined whether the participants used the geometric properties of the route (ie, distance and direction) or relied more on the landmarks.

No Landmarks. All 3 landmarks that were present during training (plant, garbage bin, and chair) were removed from the environment while keeping the start location and metric qualities of the route intact (see Figure 4A). The purpose of this test was to investigate whether the participants could locate the correct door without the landmarks present (ie, using only metric information).

Displaced Landmarks. Each landmark was displaced 1 block south from its original position during training, thus placing the landmarks in a different position relative to training (see Figure 4B). The purpose of this test was to examine whether participants would choose a door consistent with the geometric properties of the route (which had not changed) or instead choose a door consistent with the new position of the landmarks.

Extra Hallways. Extra hallways were added in the E-W direction between the existing hallways from training. To add those hallways while keeping the boundary of the environment consistent, we narrowed the walls of each block in the N-S direction (ie, up-down direction in the top view) from 3 to 1 vu (see Figure 4C). The purpose of this test was to examine whether participants would use either the overall geometry of the training route or the landmarks to find the correct door when extra hallways were added.

Different Start Location. The start location was moved 180 degrees to a mirror opposite location on the map (ie, from south-east to north-west) while all the same landmarks retained their original positions, meaning that the last landmark encountered along the route during training (the chair) was now the first landmark encountered (see Figure 4D). The purpose of this test was to examine whether participants would choose a door consistent with the geometric properties of the route (unchanged) or instead choose a door consistent with the positioning of the first landmarks encountered.

Final control trial

Following completion of all testing trials, participants experienced a final control trial in which the environment was unchanged relative to training and only 1 door choice was

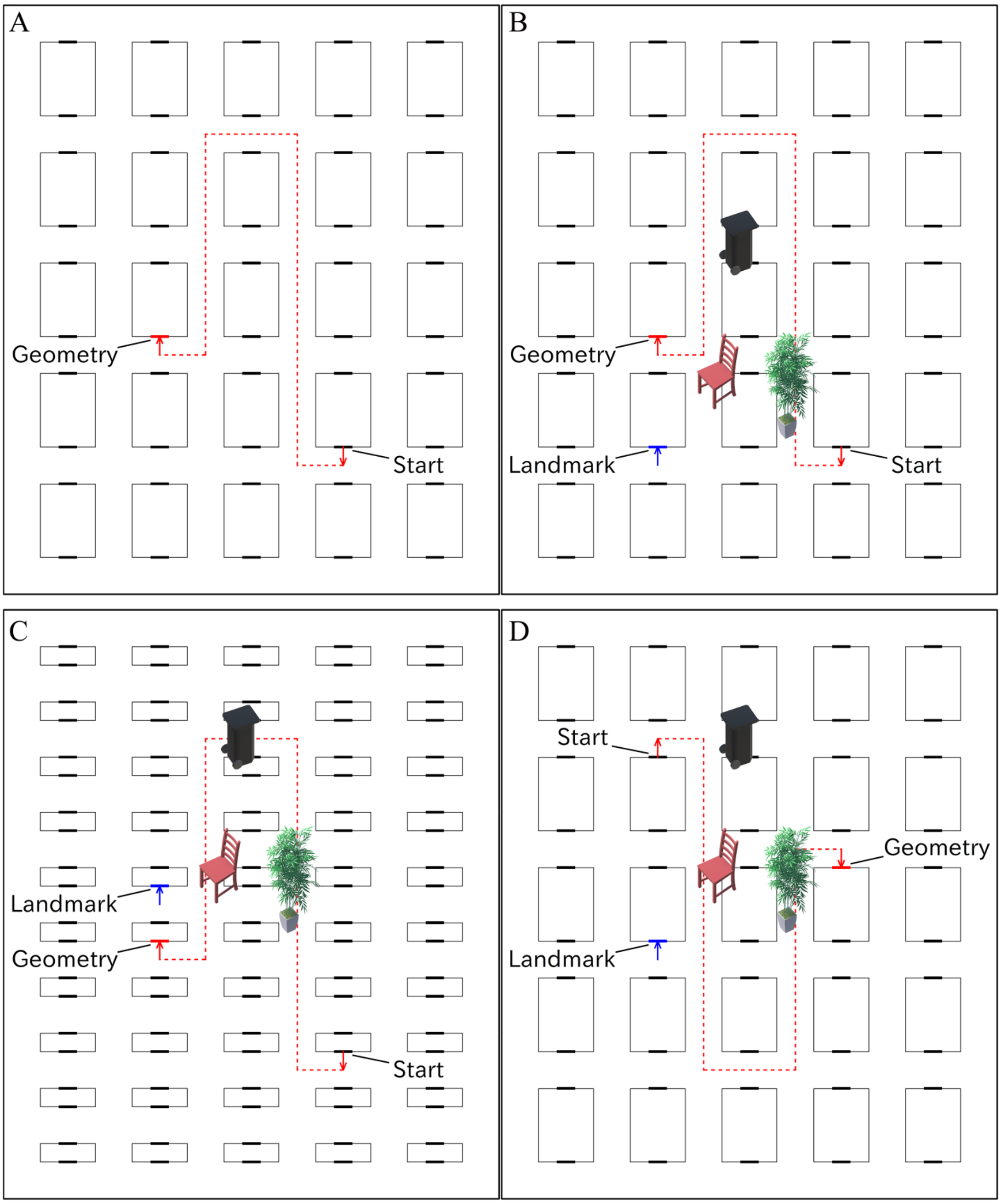

Figure 4. Schematic top-down views of the different testing conditions. The red dashed line in each testing trial indicates the route used during the training trials relative to the start location. (A) No Landmarks trials in which the tree, the garbage bin, and the chair were removed. (B) Displaced Landmarks trials in which the landmarks were displaced 1 hallway block south of their original location. (C) Extra Hallways in which extra hallways were added. (D) Different Start Location trials in which the start location was changed. Note that a geometry-based strategy translates to the correct door being rotated 180 degrees relative to training.

allowed with no verbal feedback provided. The purpose of this trial was to ensure that participants had retained the location of the correct door throughout the duration of the testing phase.

Landmark Recognition test

To ensure that all participants could recognize the landmarks they experienced during the course of the experiment, a Landmark Recognition test was included at the end of the experiment. Participants were presented with a random series of 8 landmarks displayed sequentially on the screen, of which 3 were the same landmarks from the experiment and the other 5 were distracters, and participants had to verbally indicate which landmarks they had seen previously (see Figure 5).

Data analysis

We examined spatial choices made by participants during testing trials. We defined 3 possible choices participants could make:

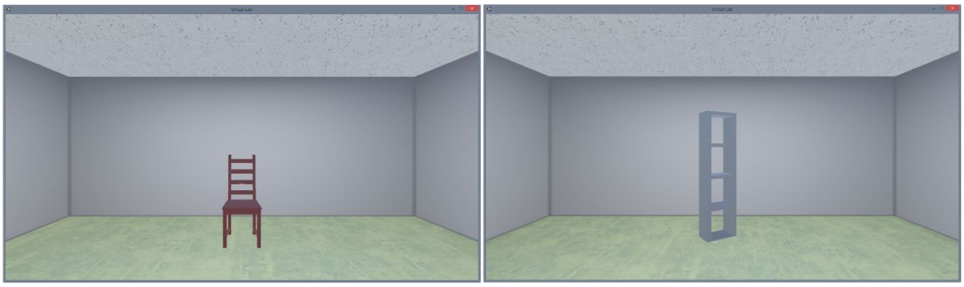

Figure 5. Two screenshots of Landmark Recognition trials. The participants saw each landmark individually and responded verbally to the researcher as to whether they saw it during one of the previous trials.

Table 1. Exact chi-square tests conducted to examine the difference between participants who used the head-mounted display and the computer monitor.

TEST CONDITION	*P*-VALUES	
	YOUNGER	OLDER
No Landmarks	1.000	1.000
Displaced Landmarks	.607	.364
Extra Hallways	.224	.891
Different Start Location	.398	.478

P-values show that there was no difference in performance based on the viewing method.

Geometry based. Participants chose the door that was correct based on the geometry of the route learned during training.

Landmark based. Participants chose the door that was correct according to its position relative to landmarks positioned along the route during training.

Incorrect. Participants chose a door that was not correct based on either the geometry of the route or the landmarks located along the route.

Results

A total of 11 participants (5 younger and 6 older adults) did not complete the experiment due to dizziness or discomfort from the HMD, and 10 other participants (5 younger and 5 older adults) were excluded as they did not choose the correct door on the second control trial. Thus, the final analysis was derived from 40 older (20 women) and 40 younger (20 women) adults. Fourteen participants (4 younger and 10 older adults) switched to the laptop display from the HMD after completion of the third training trial if they reported motion-related fatigue.

HMD vs laptop display

To determine if there was a difference between those participants who switched from the HMD to the laptop display prior to testing for each test, we ran 8 comparisons (ie, 4 testing conditions for each of the younger and older groups). Due to the number of tests, an alpha level of $P < .01$ was used as the significance level for all comparisons. Also, due to the smaller expected values (ie, less than 5) for participants who used the monitor, we employed an exact chi-square analysis for each.

The proportion of different choices made participants who used the HMD vs those who used the monitor did not differ significantly in any of the testing conditions for the younger or older adults (all *P*s > .01; see Table 1).

Men vs women

To determine whether there was a difference between men and women for each test, we ran 8 comparisons similar to that reported in section "HMD vs Laptop Display." Due to the number of tests, an alpha level of $P < .01$ was used as the significance level for all comparisons. An exact chi-square test was used except for the No Landmarks condition, in which a Pearson chi-square test was used as the least expected value was greater than 5.

The proportions of the spatial choice between men and women did not differ significantly in any of the testing conditions for the younger or older adults (all *P*s > .01; see Table 2).

Testing conditions

We investigated the types of spatial choices made by participants separately for each group (younger vs older) for each testing condition, combining those participants in each age group who used the HMD and those who used the laptop display. The null hypothesis for each condition was that the type of choices would be randomly distributed. Then, we compared the proportion of choices between the 2 age groups directly with the null hypothesis being that choice type would not differ between older and younger participants. To limit the possibility of Type I errors due to the number of tests being conducted, the significance level was set at $P < .01$ for all testing conditions. A Pearson chi-square test was used when expected values were at least 5 or an exact chi-square when they were less than 5 (see Table 3 and Figure 6).

Finally, to investigate navigation performance during the final control trial that was conducted following the completion of all testing trials, we compared the proportion of those who chose the correct door from training compared with those who did not (Pearson chi-square test).

Table 2. Chi-square tests conducted to examine the difference between men and women.

TEST CONDITION	*P*-VALUES	
	YOUNGER	OLDER
No Landmarks	.342	.110
Displaced Landmarks	.235	.523
Extra Hallways	1.000	.844
Different Start Location	.242	.413

An exact chi-square test was used except for the No Landmarks condition, in which a Pearson chi-square test was used; *P*-values show that there was no sex difference.

Table 3. The number of participants who made either geometry-based, landmark-based, or incorrect choices for each group for each testing condition.

TEST CONDITION	DOOR CHOICE	GROUP	
		YOUNGER	OLDER
No Landmarks	Geometry based	19 (1)	17 (4)
	Incorrect	21 (3)	23 (6)
Displaced Landmarks	Geometry based	8 (0)	16 (4)
	Landmark based	31 (4)	23 (5)
	Incorrect	1 (0)	1 (1)
Extra Hallways	Geometry based	15 (1)	19 (4)
	Landmark based	20 (2)	12 (3)
	Incorrect	5 (1)	9 (3)
Different Start Location	Geometry based	11 (0)	14 (3)
	Landmark based	25 (4)	16 (3)
	Incorrect	4 (0)	10 (4)

Note that participants could not make landmark-based choices during the No Landmarks condition. Numbers in parenthesis indicate those who used the laptop display during testing trials.

No Landmarks. Because all landmarks were removed, a choice to the door located in the geometrically correct position along the route was considered the only correct choice and all other choices were incorrect.

Younger adults. In total, 19 people chose the correct door based solely on the geometry of the route learned during training, whereas 21 people chose an incorrect door; this difference did not reach statistical significance at the .01 level, Pearson chi-square test: $\chi^2(1) = 0.1$, $P = .752$.

Older adults. In total, 17 people chose the correct door based solely on the geometry of the route learned during training, whereas 23 people chose an incorrect door; this difference also did not reach statistical significance at the .01 level, Pearson chi-square test: $\chi^2(1) = 0.9$, $P = .343$.

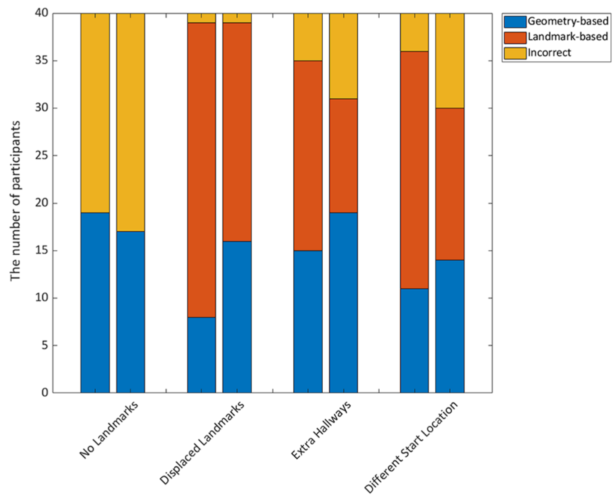

Figure 6. The proportion of the participants for each navigation strategy. For each testing trial condition, the left and right columns depict the younger and older groups, respectively.

A direct comparison did not show a significant difference between younger and older adults, Pearson chi-square test: $\chi^2(1) = 0.202$, $P = .653$. The absolute effect size $|\varphi|$ was 0.050, which is considered a small effect.[36-38] Neither younger nor older participants could reliably locate the correct door when only geometric information was available.

Displaced Landmarks. Because all landmarks were present but displaced 1 block south of their original positions during training, there were 2 possible correct doors: one based on the geometry of the route and the other based on the position of the landmarks. An incorrect choice was made to any door other than the 2 described above.

Younger adults. In total, 8 people chose the correct door according to the geometry of the route learned during training, 31 people chose the correct door according to the position of landmarks situated along the route, and 1 individual chose an incorrect door. The difference in the distribution of choices was significant, Pearson chi-square test: $\chi^2(2) = 36.95$, $P < .0005$. Pairwise comparisons showed that the number of landmark-based choices was significantly greater than that of either geometry-based choices, Pearson chi-square test: $\chi^2(1) = 13.56$, $P < .0005$, or incorrect choices, Pearson chi-square test: $\chi^2(1) = 28.13$, $P < .0005$.

Older adults. In total, 16 people chose the correct door according to the geometry of the route learned during training, 23 people chose the correct door according to the position of landmarks situated along the route, and 1 individual chose an incorrect door. The difference in the distribution of choices was significant, Pearson chi-square test: $\chi^2(2) = 18.95$, $P < .0005$. Pairwise comparisons showed that the numbers of geometry-based and landmark-based choices were each significantly greater than that of incorrect choices, Pearson chi-square test: $\chi^2(1) = 13.24$, $P < .0005$, and $\chi^2(1) = 20.17$, $P < .0005$, respectively. The difference between geometry-based and landmark-based choices was not significant, Pearson chi-square test: $\chi^2(1) = 1.26$, $P = .262$.

A direct comparison did not show a significant difference between younger and older adults overall, exact chi-square test: $\chi^2(2) = 3.852$, $P = .113$. The effect size Cramer V was 0.219, which is considered a medium effect.[36-38]

Extra Hallways. Although the total metric distance of the route remained the same as that in training, the individual blocks that formed each hallway were shortened. This manipulation resulted in 2 possible correct doors: one based on the geometry of the route and the other based on the positioning of the landmarks. An incorrect choice was one made to any other door.

Younger adults. In total, 15 people chose the correct door according to the geometry of the route learned during training, 20 people chose the correct door according to the position of landmarks situated along the route, and 5 individuals chose an incorrect door. The difference in the distribution of choices did not quite reach statistical significance at the .01 level, Pearson chi-square test: $\chi^2(2) = 8.75$, $P = .013$.

Older adults. In total, 19 people chose the correct door according to the geometry of the route learned during training, 12 people chose the correct door according to the position of landmarks situated along the route, and 9 chose an incorrect door. The difference between the choices was not significant, Pearson chi-square test: $\chi^2(2) = 3.95$, $P = .139$.

A direct comparison did not show a significant difference between younger and older adults overall, Pearson chi-square test: $\chi^2(2) = 3.613$, $P = .164$. The effect size Cramer V was 0.213, which is considered a medium effect.

Different Start Location. This trial was identical to training except that the start location was moved to a location 180 degrees from its training location. A geometry-based choice was one in which participants chose the door that was the at the 180-degree location of the correct door from training. The landmark-based choice was one in which participants simply chose the door closest to the final landmark along the route (the chair). All other choices were considered incorrect.

Younger adults. In total, 11 people chose the correct door according to the geometry of the route learned during training, 25 people chose the correct door according to the position of landmarks situated along the route, and 4 people chose an incorrect door. The difference among the choices was significant, Pearson chi-square test: $\chi^2(2) = 17.15$, $P < .0005$. Pairwise comparisons showed that the number of landmark-based choices was significantly greater than that of incorrect choices, Pearson chi-square test: $\chi^2(1) = 15.21$, $P < .0005$, but did not quite reach significance compared with geometry-based choices, Pearson chi-square test: $\chi^2(1) = 5.44$, $P = .02$. The difference between geometry-based choices and incorrect choices was not significant, Pearson chi-square test: $\chi^2(1) = 1.26$, $P = .071$.

Table 4. Performance of both younger and older participants during the final control trial.

CHOICE	GROUP	
	YOUNGER	OLDER
Correct door	35 (3)	31 (6)
Incorrect door	5 (1)	9 (4)

Results show that both groups chose the correct door significantly more than the incorrect door. Numbers in parentheses indicate those participants who used the laptop display.

Older adults. In total, 14 people chose the correct door according to the geometry of the route learned during training, 16 people chose the correct door according to the position of landmarks situated along the route, and 10 people chose an incorrect door. The difference in the distribution of choices was not significant, Pearson chi-square test: $\chi^2(2) = 1.4$, $P = .497$.

A direct comparison did not show a significant difference between younger and older participants, Pearson chi-square test: $\chi^2(2) = 4.907$, $P = .086$. The effect size Cramer V was 0.248, which is considered a medium effect.

Final control trial

The navigation performance during the control trial conducted following testing is summarized in Table 3. Only 1 door was considered correct during this trial, whereas choices to all other doors were considered incorrect. Both younger participants, Pearson chi-square test: $\chi^2(1) = 22.5$, $P < .0005$, and older participants, Pearson chi-square test: $\chi^2(1) = 12.1$, $P = .001$, chose the correct door more often than the incorrect door (see Table 4).

A direct comparison did not show a significant difference between younger and older participants, Pearson chi-square test: $\chi^2(1) = 1.385$, $P = .239$. The absolute effect size $|\varphi|$ was 0.132, which is considered a small effect.

Landmark Recognition testing trial

With the exception of 1 younger adult (who responded with 1 error), all participants performed perfectly during this trial supporting the fact that participants correctly recalled all the landmarks they saw during the trials.

Discussion

The objective of this study was to investigate whether the encoding of geometry and features differed between younger and older adults. This was examined through the use of systematic manipulations of the environment, after confirming that the participants learned the predetermined training route.

During training, both younger and older adults learned to search for a correct door located within a virtual hallway complex by following a short, predetermined route; the route included 3 landmarks and required participants to make turns along the way. Testing trials, in which participants were instructed to locate the correct door when either the geometric properties of the hallways or the landmarks were manipulated, revealed a general finding that both age groups relied more strongly on landmarks to maintain an accurate sense of position. However, younger adults showed an overall tendency to adapt better to the testing manipulations compared with older adults.

Surprisingly, during the *No Landmarks test* when only the geometry of the route was available, both younger and older adults struggled to locate the correct door when relying on geometry alone, with approximately half of them choosing an incorrect door. This finding suggests that both age groups needed at least some landmark cues to reliably use the geometry of the route. During the *Displaced Landmarks test*, the landmarks were available but each one was displaced 1 block south of the original position it had occupied during the training phase, whereas the overall geometry of the route remained unchanged. This manipulation presented 2 clear strategies for participants; they could choose a door based on following the learned route (geometry based) or they could choose a door based on the new positions of the landmarks (landmark based). Results showed that younger participants readily used the landmarks to choose a door consistent with the new landmark positions, whereas older participants divided their choices between a door consistent with geometry and one consistent with landmarks. Although neither group relied on geometry to any appreciable extent, the younger adults were more likely to adopt a landmark-based strategy, whereas the older adults were not, at least when the landmark positions were displaced from the original training route. This finding is consistent with previous research showing that older adults have greater difficulty using landmarks within an allocentric framework.[7,13,19,20,23]

During the *Extra Hallways test*, the blocks that formed the hallways were shortened, allowing more blocks to fit within the same distance of the original training route; a geometry-based choice in this context was one made to the door that preserved this exact route distance, whereas a landmark-based choice was to a door closest to the final landmark (the chair). Neither group showed any preference for the landmark-based or the geometry-based strategy during this test.

During the *Different Start Location* test, participants started the trial on the end leg of the training route so that the last landmarks they encountered during the training trials (the garbage bin and the chair) were now the first landmarks encountered during the test trial. Participants could choose the door closest to the chair (a landmark-based choice) or continue along the route and choose a door on the opposite side (a geometry-based choice). Results showed that younger adults adopted a landmark-based strategy, whereas older adults did not favor either strategy and collectively made more errors (ie, choosing doors that were incorrect according to both strategies). This suggests that younger participants' memory for the route may have been more flexible, so that when the order of the landmarks was effectively reversed, they could still recognize the landmark most closely associated with the correct door even though it was always the last landmark they encountered during training.

The fact that younger and older participants could accurately locate the correct door during control trials, when the environment was unchanged relative to training, shows that the environment was sufficiently learned and retained by both groups. However, when changes to the environment still included landmarks, younger participants could use them, whereas older participants could not. These results are consistent with previous navigation studies showing that older people perform more poorly compared with younger people when relying on allocentric landmark-based strategies to navigate.[7,13,19,22,23,39] Overall, the younger participants in our study seemed more able to adapt to alterations of the environment, providing that landmarks were still available. Neither younger nor older participants could find the correct door using geometric cues alone.

Why might older people form less stable spatial memories of recently learned environments? One possibility is that working memory capacity diminishes with age.[40,41] Less capacity might not allow the older participants to remember the order of the landmarks along the route, and thus it could be difficult to recall during testing trials. Given that our spatial environment was fairly small (only 3 landmarks) and participants were allowed multiple training trials, working memory load was relatively light during our task. A related possibility is reduced hippocampal volume and the corresponding reduction in function as a natural consequence of aging.[42-48] The hippocampus is critical for memory formation, particularly in the integration of the different elements that comprise an event; importantly, it has also been suggested to play a role in working memory maintenance.[49] Specific to spatial memory, the hippocampus is essential because it houses place cells which integrate inputs from cells in nearby cortical tissue that are dedicated to the neural reconstruction of the outside world, which is critical for forming allocentric spatial memories.[42,43,50] A reduction in hippocampal volume could prevent encoding the location of each landmark in relation to the target location. Neuroimaging studies have confirmed that increased activation in hippocampal cortical areas is associated with better recall of the spatial layout of an environment.[42] For example, when navigation performance was tested using a virtual Morris Water Maze, younger participants (mean age: 26.1 years) outperformed elderly participants (mean age: 77.6 years) on measures of allocentric memory (ie, hippocampal dependent), with poorer results being associated with a corresponding reduction in hippocampal volume as shown via neuroimaging.[45]

One concern with our study is the number of people who experienced motion-related fatigue or dizziness when using the HMD; a total of 5 younger and 7 older adults could not complete the experiment, whereas other 4 younger and 10 older adults were able to continue only after switching from the HMD to a laptop display. This is contrasted with previous experiments using the same VRNChair and HMD in which no participants reported dizziness or had to quit the experiment for this reason; the virtual environments used in the previous experiment were either comparatively much smaller (a single room) than the current experiment,[5] or large and empty.[26,27] Due to the space needed for the VRNChair to effectively move the participant within a larger virtual space, the movement translation from real to virtual was set at a 1:2 ratio (ie, a movement of 1 m in the real world translated to 2 m in the virtual world). In combination with the relatively narrow hallways of our environment (2 virtual meters in width), some participants may have experienced an unnaturally fast sense of optic flow as a result. However, it must be remembered that participants were able to freely slow their speed down if they felt they were moving too fast. Future studies should address the degree that optical flow speed may contribute to motion-related fatigue in VR environments.

Overall, our results are in agreement with other studies, showing that a general difference in navigation ability between younger and older adults may be one of flexibility.[10,13,21,51,52] The fact that both groups overwhelmingly chose the correct door during the final control trial shows that the route was successfully learned during training, probably as a combination of encoding geometry and landmarks together. However, younger adults adapted to environmental changes more readily than older adults, and they did this by defaulting to the use of landmarks to guide their choices. Older adults, however, showed more difficulty adjusting to environmental changes, suggesting that their encoding of the route during training was more rigid and resistant to change when compared with younger adults. These results suggest that, as people age, the encoding of spatial information becomes less malleable. The implication is that older adults may have more difficulty remembering previously learned routes in which individual landmarks have undergone either removal or noticeable change. In addition, they may also find it more difficult to reorient to a known route when it is approached by them from a less well-known vantage point.

Author Contributions

K.K., J.F.R, D.M.K. and Z.M. contributed to the design of the experiment. K.K. performed the experiment. K.K., J.F.R, D.M.K. and Z.M. contributed to the analyses, and to the writing of the manuscript.

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