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Analysis of Spatiotemporal Features in Virtual Navigation Game Across Different Age Groups: Quantitative research

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Abstract

Background: Virtual reality (VR) navigation games are increasingly employed to investigate human navigational behavior and cognitive performance under controlled spatial conditions. However, there is a lack of empirical research on how spatial configurations and individual cognitive abilities influence wayfinding performance, particularly across different age groups.

Objective: This study aims to investigate the critical associations between environmental factors (external factors) and cognitive abilities (internal factors) in shaping navigational behavior performance in wayfinding games across different age groups.

Methods: We designed a virtual navigation game and recruited two groups, younger adults (n = 18) and older adults (n = 21), to complete identical goal-directed wayfinding tasks. Prior to the formal experiment, cognitive abilities were assessed through questionnaires, and pre-training was conducted to ensure participants were familiar with navigating within the virtual environment (VE). In this study, navigation efficiency was used as the primary spatiotemporal feature, and Spearman's rank correlation was employed to examine its relationship with cognitive abilities. To quantify the spatial structure of the VE, we applied Space Syntax Analysis (SSA), including both Axial Map Analysis (AMA) and Visibility Graph Analysis (VGA), to investigate the associations between navigation efficiency and spatial configurations. Additionally, the Mann-Whitney U test was used to compare navigation behavior differences between the age groups from a spatiotemporal perspective.

Results: Our results revealed that navigation behavior performance, particularly navigation efficiency, was significantly influenced by cognitive abilities and strongly correlated with several cognitive tests: the Montreal Cognitive Assessment ($r = 0.495$, $p < 0.05$), Part A of the Trail Making Test ($r = -0.761$, $p < 0.01$), and the Mental Rotation Test ($r = 0.848$, $p < 0.01$). Additionally, aging leaded to a significant decline in navigation efficiency ($Z = -4.285$, $p < 0.001$). Affected by the surrounding environmental factors of the axial path, navigation efficiency was closely related to connectivity ($r = 0.675$, $p < 0.05$), integration ($r = 0.749$, $p < 0.01$), and depth ($r = -0.646$, $p < 0.05$) derived from AMA. The integration experienced, based on participants' movement trajectories and VGA, showed significant age differences ($Z = -2.097$, $p < 0.05$) and was correlated with navigation efficiency ($r = -0.366$, $p < 0.05$).

Conclusions: The spatiotemporal features of virtual navigation games are shaped by both cognitive abilities and environmental structure. There is ample evidence confirming that navigation games have great potential to serve as an effective cognitive assessment tool. Our findings also reveal that younger participants or those with better cognitive abilities tend to prioritize traversing lower-integrated areas to enhance navigation efficiency, leading to more optimal navigation strategy.

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KEYWORDS

Spatial navigation; Environmental structure; Serious games; Space syntax; Cognitive assessment; Aging

Introduction

Background

With the ongoing process of urbanization, spatial navigation, the ability to determine an appropriate route and purposefully move toward a specific destination, has increasingly become a considerable challenge, particularly for older adults[1, 2]. Serious Games (SGs) leverage entertaining activities to facilitate learning and training in specific areas and tasks[3]. By gamifying navigation tasks, SGs provide a fun and engaging way to train and assess navigational abilities[4].

Over the past decades, benefiting from the progress of computer technology, spatial navigation studies have undergone significant innovation. Early navigational experiments focused on paper-and-pencil tests of spatial memory, such as mazes or maps[5, 6]. Evidently, such navigation simulation fails to accurately replicate real-world navigation experiences, both in terms of spatial information acquisition and the overall complexity of the task. To achieve more realistic behavior performance, researchers complemented experiments conducted in real-world environments[7, 8]. However, these studies are time-consuming and expensive, requiring highly trained professionals to administer, and impose a significant physical burden on elderly individuals or those with cognitive impairments[9].

Recent advancements in virtual reality (VR) technology have enabled the creation of highly immersive virtual environment (VE) that closely replicate the real world with high fidelity[10, 11]. Efficient VR-SGs are regarded as valuable tools for assessing and enhancing spatial navigation. Researchers can precisely control environmental variables such as landmark distribution, path complexity, spatial layout, and visual cues in immersive VEs[12], making it possible to investigate navigation behavior under the influence of different factors. Moreover, VR technology allows for the collection of a wide range of behavioral data, such as completion time, movement trajectories, error rates, and specific behavioral reactions at given moments[13]. By constructing immersive VEs and task framework, researchers have developed a variety of experimental paradigms designed for specific navigation tasks, including the Virtual Floor Maze Test (VR-FMT) [14], Morris Water Maze task[15], and object-location memory task[16, 17].

VR-SGs navigation tasks allow good ecological validity[18]. Montello *et al*[19] proposed that the navigation task consists of two main components: locomotion and wayfinding. Locomotion refers to the physical execution of movement in the space, whereas wayfinding is involved in determining and planning a route to a desired destination[20]. Effective spatial navigation relies on the integration of multiple abilities, including visual perception, spatial orientation, learning, and memory[21]. Therefore, the decline of the navigation ability is attributed to many factors, such as reduced familiarity with previously known environments[22, 23], difficulties in recognizing landmarks[24], and impairments in recalling complex spatial scenes[25]. Evidence from previous studies has indicated that behavioral performance in navigation tasks is influenced by both extrinsic factors (e.g., spatial properties of the environment, visual accessibility of landscape)[26, 27] and intrinsic factors (e.g., age, education level, personality traits)[28, 29]. These factors shape how individuals collect and interpret spatial information, determine their navigation strategy preferences, and impact cognitive abilities and decision-making patterns.

In contemporary urban environments, the prevalence of densely packed buildings with homogeneous architectural designs has led to an increased incidence of disorientation and difficulty navigating. Additionally, irregular street networks and frequent modification of constructions and roads tend to disrupt the formation of cognitive maps and hinder spatial orientation[30]. Simultaneously, topographical disorientation (TD), which is associated with cognitive decline, has emerged as a critical internal factor in wayfinding challenges. It is also recognized as one of the earliest indicators of mild cognitive impairment (MCI) and Alzheimer’s disease[31]. Individuals experiencing TD tend to confine themselves to familiar environments, resulting in critical limitations on their ability to engage in daily activities[32]. Neuroscientific evidence underscores the vulnerability of the entorhinal cortex (EC), a crucial region involved in spatial navigation, to neurodegenerative processes[33]. Grid cells within the EC, which are essential for spatial representation and path integration, exhibit notable functional impairments as individuals age. These age-related deficits in grid cell activity may disrupt the formation of stable cognitive maps, leading to difficulties in orientation, route planning, and wayfinding[16]. However, there is a lack of empirical research on how spatial configurations and individual cognitive abilities influence wayfinding performance, particularly across different age groups.

The safe and adaptable of VR-SGs technology has made it a popular tool for assessing and enhancing spatial navigation abilities for elderly or cognitive-impaired participants[34, 35]. In this research, we designed a virtual urban environment and recruited two groups younger adults and older adults, to complete identical goal-directed wayfinding games. Prior to the formal experiment, cognitive abilities were assessed through questionnaires, and pre-training was conducted to ensure participants were familiar with navigating within the VE. To quantify the spatial structure of the VE, we applied Space Syntax Analysis (SSA) [36], including both Axial Map Analysis (AMA) [22] and Visibility Graph Analysis (VGA) [27, 37, 38], to investigate the associations between navigation behavior and spatial configurations. Furthermore, the study also reveals differences in navigation behavior patterns and environmental preferences across different age groups, highlighting how both external and internal factors influence spatial navigation.

Figure 1. Pre-training phase: Top-down view of the scene (middle) and views of the target from four different locations (left, right).

Participants

The study was conducted with 21 healthy older adults (14 males, 7 females) aged 65 to 80 years (mean age: 71.79 ± 4.57), and 18 healthy younger adults (10 males, 8 females) aged 21 to 33 years (mean age: 26.50 ± 2.99). All participants had no history of neurological or psychiatric disorders. Older participants were recruited from the community at least 65 years old and able to complete daily activities independently. One older participant with a history of cerebral hemorrhage was excluded prior to the study, and another withdrew due to intolerance to VR-induced dizziness. Younger subjects were selected from the university. Prior to the commencement of the testing phase, all participants provided consent forms. Additionally, individual information, encompassing age, gender, educational background, and prior VR experience, was systematically gathered from each participant.

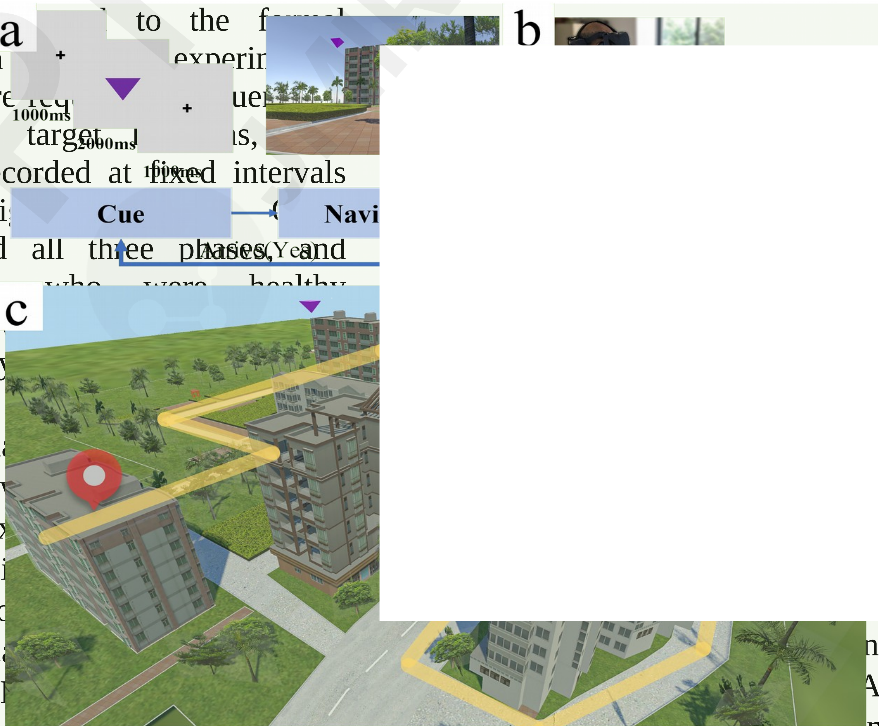
potential anxiety associated with navigating the virtual scenario[39].

Given the extensive spatial requirements for virtual navigation games, and recognizing that certain older participants may face limitations in sustained walking, we adopted a combined navigation control scheme using both the grip controller and the facing direction. Participants were instructed to press the touchpad on the controller to move forward in the direction they were facing, thereby controlling the movement of their avatar within the VE. For directional changes, the turning angle of the participant's physical movement was mapped to the virtual reality scene in a one-to-one ratio, ensuring an accurate correspondence between real-world and virtual orientations. In addition, the HMD offers advanced features such as a higher refresh rate, superior resolution, and reduced latency, which greatly improve the smoothness of viewpoint transitions. These enhancements collectively serve to effectively reduce the incidence of motion sickness[40].

Experimental Procedure

The experiment consisted of three phases: (1) neuropsychological assessment, (2) pre-training, and (3) formal experiment. The neuropsychological assessment phase aimed to evaluate the cognitive abilities of elderly participants using standardized measures of general cognitive skills and empirically validated tests. During the pre-training phase, participants were instructed to navigate freely within the VE for 15 minutes. Navigation proficiency was considered achieved when participants demonstrated the ability to independently and fluently operate the controller and

Figure 2. Formal experiment, including the experimental procedure, participant experience, and the shortest route of all trials.



navigate to designated target locations, qualifying them to ... to the formal experimental phase. In ... experim... phase, participants were req... navigate to multiple target... s, spatiotemporal data recorded at fixed intervals throughout the navi... participants completed all three phases, and younger participants who were healthy university students ... cognitive function, only ... and 3.

Before the formal n... cognitive functioning ... Mini-Mental State Ex... and the Montreal Cogni... [42]. Nonverbal memo... using the Delayed Rec... Osterrieth Complex ... while visuospatial functioning was evaluated through the Copy condition (ROCF- ... ne executive ... A of the Trail Making Test (TMTA) was administered[44].

Additionally, spatial rotation ability was assessed using a standardized mental rotation test (MRT) [45]. These assessments provided a comprehensive cognitive profile for each participant prior to engagement in the virtual navigation experiment.

During the pre-experimental phase, identically shaped but differently colored target objects were placed at various locations within the VE (Figure 1). Participants were instructed to memorize the spatial locations corresponding to each colored object. During the formal experimental phase, five target locations previously encountered during the training phase were used (Figure 2c). Target locations were presented in a fixed sequential order to reduce variability introduced by randomization. Each trial began with a fixation cross (1000ms), followed by the target cue (2000ms), and another fixation cross (1000ms), and then participants were required to navigate to the designated target location (Figure 2a). Upon reaching the target, the current trial was concluded, and the next trial was automatically initiated. This sequence continued until all tasks were completed. Participants were instructed to navigate as quickly and accurately as possible (Figure 2b) and a congratulatory animation was displayed after each trial to prevent boredom.

Environmental structure

Space Syntax provides a robust and systematic framework for examining the spatial arrangement of environments and the interrelationships between spaces. This methodology has been extensively applied to explore how spatial configurations affect human behaviour[46-48], particularly how individuals encode, represent, and retrieve spatial information during navigation. In this study, both AMA and the VGA of the VE were carried out using the DepthmapX software.

Axial Map Analysis

The axial map provides a graphical representation of spatial structure, where streets within an urban environment are abstracted as axial lines, defined as the minimal set of longest straight lines of sight from a given location[49, 50]. These lines collectively cover the entire space, capturing all possible movement paths. Based on the 2D layout of the VE street network, we constructed an axial map with a total of 12 axial lines delineated (Figure 3). For analytical purposes, key metrics such as axial integration, axial connectivity, and axial choice were calculated to characterize the accessibility and flow potential of individual environmental segments. Additionally, the metric of intelligibility was used to assess the extent to which the spatial configuration supports cognitive understanding of the environment.

Visibility Graph Analysis

VGA provides an analytical approach for quantifying the spatial characteristics of an environment by assessing the extent to which any given point within the space is visible from any other point[51]. In this study, the structural layout of the VE was first modelled using AutoCAD. Subsequently, a 1 m × 1 m grid was generated in DepthmapX to perform the analysis. This process enables the computation of key spatial metrics at each node, including visual integration, visual connectivity, visual mean depth, and visual intelligibility.

Statistical Analysis

Spatiotemporal data analysis

After acquiring spatiotemporal data for each participant at a fixed sampling frequency, we compute the average speed at each recorded location. To segment the navigation states of each recorded point, we apply the K-Means clustering algorithm to classify the speed data into three distinct categories: Wayfinding, Transition, and Moving. The cluster with the lowest centroid is labeled as the wayfinding state, and the highest centroid as the Moving state. Considering that individual navigation abilities are influenced by factors such as personality, gender, and prior experience, the clustering was conducted separately for each participant. This relative segmentation strategy allows for the identification of areas within the environment where participants tend to slow down or linger, without relying on absolute speed thresholds. Therefore, this method reduces potential bias introduced by inter-individual variability.

Navigation Efficiency

Navigation Efficiency is defined as the ratio of effective navigation time (moving time and transition time) to the total duration of the navigation task (navigation time), and is calculated using the following formula:

$$Navigation\ efficiency = \frac{(Moving\ time + Transition\ tin}{Navigation\ time}$$

This metric serves as an indicator of the capability to navigate effectively within the environment. Higher values reflect a more streamlined and goal-oriented navigation process, characterized by reduced time spent on behaviors such as hesitation, reorientation, or uncertainty. By quantifying navigation efficiency, we can evaluate the extent to which individuals construct accurate cognitive maps and adopt effective spatial strategies during navigation tasks.

Behavioral metrics in each axial line

Based on the 2D layout of the VE street network, 12 axial lines were defined for subsequent axial analysis, with colored routes indicating the shortest navigation paths under different task conditions (Figure 3). Along each axial line, several behavioral metrics for older adults were quantified, including traversed distance, average speed, navigation time, wayfinding time, and navigation efficiency.

Figure 3. The axial map constructed from the 2D layout of the VE street network.

Figure 4. Spatial density distribution of wayfinding points (Left: older adults; Right: young adults).

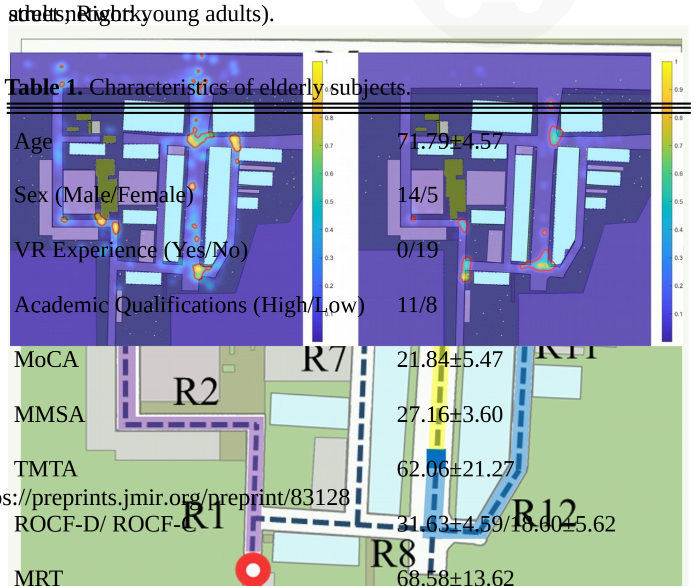


Table 1. Characteristics of elderly subjects.

Age	71.79±4.57
Sex (Male/Female)	14/5
VR Experience (Yes/No)	0/19
Academic Qualifications (High/Low)	11/8
MoCA	21.84±5.47
MMSA	27.16±3.60
TMTA	62.06±21.27
ROCF-D/ ROCF-C	31.63±4.59/18.60±5.62
MRT	68.58±13.62

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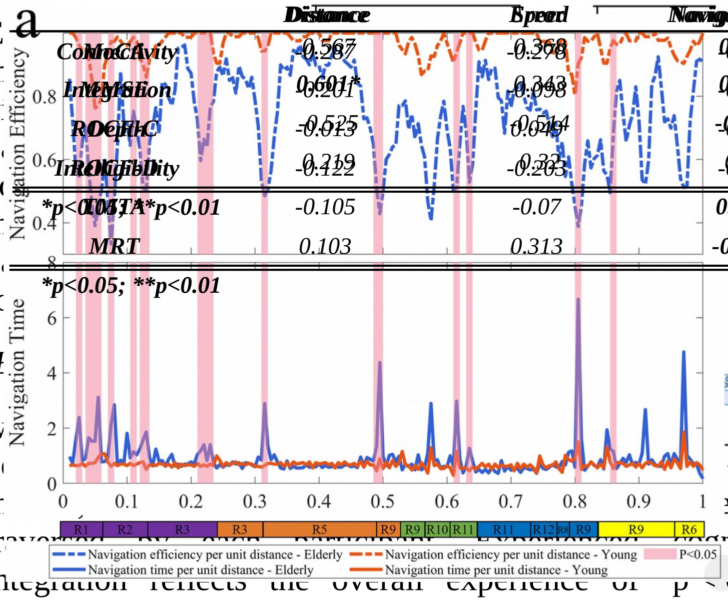
Experienced integration



integration reflects the overall experience of spatial integration during wayfinding and captures the dynamic interaction between environmental structure and navigational behavior.

Results

Participants

All 19 older participants and 18 young participants successfully completed the experiment without experiencing severe motion sickness. Table 1 summarizes the cognitive characteristics of the older group, including the means and standard deviations for various cognitive assessment scales. Notably, none of the participants had prior experience with VR technology, which reduced potential biases associated with equipment familiarity.

After clustering the data, points labeled as wayfinding exhibited clear spatial concentration and age-related differences (Figure 4). This spatial density map visualizes wayfinding patterns, offering an intuitive overview of participants' spatial behavior based on spatiotemporal features. The red-outlined areas indicate the top 1% of regions with the highest density values, highlighting zones of intensified wayfinding activity within the virtual environment.

The correlation between navigation ... abilities in

	Distance	Speed	Navigation Time	Wayfinding Time	Navigation Efficiency
MoCA	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MMSE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
ROCF-C	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TMTA	-0.105	-0.07	**0.503***	**0.716****	**-0.761****
MRT	0.103	0.313	**-0.526***	**-0.751****	**0.848****

*p<0.05; **p<0.01

... shows strong correlations with several cognitive measures, including TMTA (r = 0.716, p < 0.01), MoCA (r = -0.549, p < 0.05), ROCF-C (r = -0.588, p < 0.05), MMSE (r = -0.458, p < 0.05) and MRT (r = -0.751, p < 0.01). Additionally, navigation efficiency demonstrates significant associations with MoCA (r = 0.495, p < 0.05) and ROCF-C (r = 0.658, p < 0.05) scores, and particularly strong correlations with TMTA (r = -0.761, p < 0.01) and MRT (r = 0.848, p < 0.01). These findings confirm that cognitive abilities play a crucial role in influencing navigation efficiency (including navigation time and wayfinding time). Additionally, they indirectly suggest that wayfinding time and navigation efficiency can serve as reliable indicators for assessing cognitive abilities in older individuals.

Analysis of age-related decline in wayfinding ability

The Mann-Whitney U test is employed to assess differences in navigation performance between age groups (Figure 5). Compared to younger participants, older adults, who exhibited significantly lower cognitive ability, demonstrated significantly longer navigation time (Z = -4.771, p < 0.001) and wayfinding times (Z = -4.315, p < 0.001), as well as reduced navigation efficiency (Z = -4.285, p < 0.001).

Above metrics reflect participants' overall wayfinding performance. However, navigation behavior is not solely influenced by internal factors such as cognitive ability. It also varies depending on the location of participants within the VE. Figure 6a illustrates differences in the navigation process across age groups during the formal experiment. To investigate this, participants' spatial positions are mapped onto the shortest navigation routes (excluding trials involving route errors), and the time spent per unit distance is calculated for each individual. Based on these data, we plot curves of navigation time and navigation efficiency for each age group. Furthermore, a permutation test is conducted on navigation efficiency within each unit distance between older and young adults. The shaded regions on Figure 6b corresponding areas where significant differences are observed ($p < 0.05$) on Figure 6a, revealing spatial zones where age-related differences in navigation behavior are most pronounced. These results highlight age-related differences in spatial behavior and reinforce the utility of these behavioral metrics as sensitive indicators of cognitive function.

The relationship between navigation behavior and environmental characteristic

The influence of environmental characteristic on navigation performance is analyzed from the perspective of spatial configuration using both AMA and VGA of the VE. In the axial analysis, we investigate the relationships between behavioral metrics, such as traversal distance, speed, navigation time, wayfinding time, and navigation efficiency, along each axial line for all older participants and axial parameters. Spearman's rank correlation analysis reveals that navigation time and navigation efficiency are significantly correlated with the connectivity, integration, and depth of the corresponding axial lines (Table 3).

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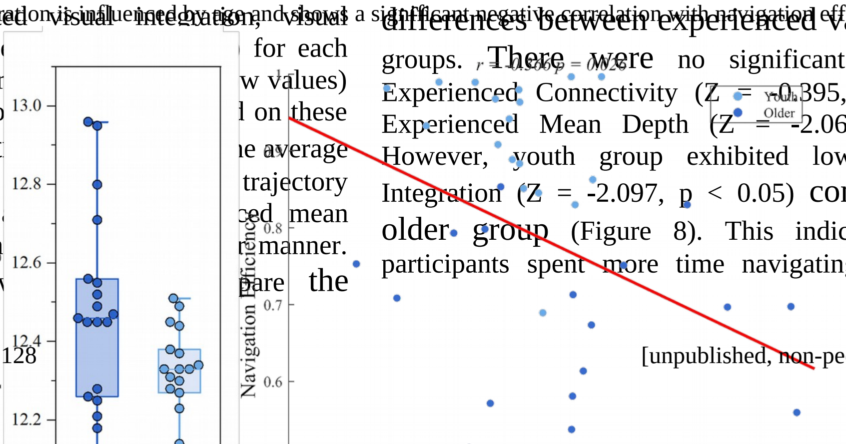
Figure 8. Experienced Integration is influenced by age and shows a significant negative correlation with navigation efficiency.



Using VGA, we computed visual integration, visual connectivity, and visual m[...] for each node within VE, the range r[...] w values) through green to yellow (fo[...] l on these quantitative spatial met[...] he average integration value along [...] trajectory (experienced integration), [...] ced mean depth and experienced co[...] r manner. Mann-Whitney U tests [...] pare the differences between experienced values across age groups. There were no significant differences in Experienced Connectivity ($Z = -0.395$, $p = 0.693$) or Experienced Mean Depth ($Z = -2.066$, $p = 0.059$). However, youth group exhibited lower Experienced Integration ($Z = -2.097$, $p < 0.05$) compared to the older group (Figure 8). This indicated that older participants spent more time navigating through high-integration segments, and the youth were willing to traverse low-integration areas to enhance navigation efficiency. In addition, Pearson's correlation analysis reveals a significant negative correlation between navigation efficiency and experienced integration across all participants ($r = -0.366$, $p < 0.05$, $n = 37$), suggesting that higher experienced integration is associated with lower navigation efficiency.

Discussion

Summary and Explanation of Findings

This study aims to investigate the critical associations between environmental factors (external factors) and cognitive abilities (internal factors) in shaping navigational behavior performance in wayfinding games across different age groups. Ample evidence suggests that individuals' performance in navigation games, particularly navigation efficiency, is significantly influenced by both cognitive abilities and environmental structure. Moreover, navigation games demonstrate great potential as an effective tool for cognitive assessment.

The behavioral metrics employed in this study, including traversal distance, number of errors, and navigation time are widely used in human navigation research[14, 52]. Spatiotemporal representation has always been a key focus in studying behavior in navigation games. We calculated relative speed thresholds individually for each participant and classified each spatiotemporal data point into different states, distinguishing our approach from traditional classification methods that rely on absolute thresholds[53]. This method ensures that each identified wayfinding region reflect the participant's unique navigation behavior, thereby minimizing potential confounding effects arising from differences in operating habits, familiarity with VR environments, and other individual factors unrelated to cognitive ability.

Wayfinding encompasses all of the ways in which people orient themselves in physical space and navigate from place to place. As anticipated, wayfinding ability, as a cognitive element of the navigation process, is effectively captured by parameters such as wayfinding time and navigation efficiency, both of which are shown to be sensitive indicators of cognitive capacity in the current study. As summarized in Table 2, cognitive scales including the MMSE, MoCA, ROCF-C, TMTA, and MRT exhibited robust correlations with these navigation metrics. Among these, the MoCA and MMSE are well-established tools for comprehensive cognitive assessment; the TMTA is primarily associated with executive functioning; ROCF-C performance reflects graphic copying abilities sensitive to geometric figure processing; and the MRT specifically measures the ability to mentally rotate objects in space. These findings reveal the impact of cognitive abilities on quantifiable wayfinding behavior. On the other hand, wayfinding performance also reflects the level of cognitive ability, reinforcing the notion that longer wayfinding times and lower navigation efficiency are indicative of weaker cognitive performance. Therefore, appropriately designed navigation games possess great potential as an effective tool for cognitive assessment.

Human navigation in outdoor environments involves a series of distinctive behaviours, such as retracing steps, hesitation, and reorientation[54]. These behaviors become particularly evident in complex spatial settings where individuals must process environmental cues and make directional decisions. Wayfinding time serves as a key indicator for revealing navigation uncertainty, effectively pinpointing locations where external environmental factors impact individuals' sense of directional uncertainty (Figure 4).

After excluding trials with route errors, we observe that prolonged wayfinding times were predominantly concentrated in the turning areas of the path, and the starting or ending locations of each trial. These highlighted areas in the figure represent regions where participants are more likely to encounter decision-making bottlenecks, experiencing uncertainty in selecting the correct path. Furthermore, integrating the analysis in Figure 6, we find significant differences in navigation preferences between younger and older participants in certain regions. Overall, younger participants exhibit a more proactive and goal-directed navigation strategy, primarily demonstrated by their tendency to observe the environment and gather clues after the start of the trial, then plan their routes accordingly. In contrast, older participants tend to adopt a stimulus-response navigation pattern[55, 56], making directional decisions only upon reaching an intersection rather than engaging in preemptive route planning. As a result, older participants display hesitation at nearly every decision point. This phenomenon likely reflects age-related declines in spatial working memory and executive function, impairing their ability to efficiently integrate spatial cues. Additionally, in wayfinding areas, perception-driven information-seeking behaviours may lead to increased exploration, longer times spent searching for landmarks or other environmental cues, and consequently, diminished navigation performance[57, 58]. This effect is particularly pronounced among older adults[8].

Space Syntax Analysis is employed to examine the relationship between navigation patterns and the spatial configuration of the environment. AMA and VGA both quantify spatial configurations, with the former focusing on axial lines and the latter on spatial visualization, each providing unique insights into spatial structure. The results from AMA show that participants exhibit higher navigation efficiency and shorter navigation time in axial lines characterized by high integration, strong connectivity, and lower depth. This is Consistent with previous research findings, which emphasizes that highly integrated and connected axial lines are associated with better directional pointing by participants[22]. Furthermore, this research provides additional evidence that axial lines with greater connectivity and integration create more accessible and interconnected pathways, which can potentially reduce cognitive load and facilitate more efficient decision-making during navigation.

Similarly, the application of VGA in wayfinding research also underwent extensive development. In this study, experienced integration is especially important, as it quantifies the participants' overall behavioral response to environmental influences. This value describes the extent to which participants concentrate their exploration on areas with varying levels of integration. The youth group exhibited lower experienced integration compared to the older group. Considering the cognitive ability differences between the two groups, we hypothesize that this metric not only reflects the structural affordances of the environment but also encodes cognitive engagement with these environmental characteristics.

To further explore this, we examined the relationship between experienced integration and navigation efficiency across all participants. Notably, within this VE, lower levels of experienced integration are associated with higher navigation efficiency. This finding suggests that under goal-directed navigation tasks, superior navigation performance may derive not from broad exploration of highly integrated areas, but rather from the strategic prioritization of direct, streamlined routes. Additionally, these results also highlight the potential of navigation efficiency as a comprehensive indicator that simultaneously captures both intrinsic (i.e., individual cognitive capacity) and extrinsic (i.e., environmental structural) influences on navigation performance. These results align with and extend prior evidence regarding age-related differences in navigation strategies. Areas with higher integration contribute to a more favorable navigation experience, as the form of mental representations of an environment is influenced by the alignment between exploration patterns and the spatial syntax of that environment [59] . Additionally, it is generally recognized that humans tend to favor well-integrated paths to gather visual cues and reinforce route memory. However, in pursuit of higher navigation efficiency, younger participants or those with better cognitive abilities in our study appeared to prioritize speed and efficiency over environmental exploration when engaged in goal-directed navigation. As a result, they frequently bypassed high-integration regions in favor of more direct routes. This type of navigation strategy, based on a central-point approach, has also been validated in prior research[46].

Together, SSA underscores the critical role of spatial configuration, such as the spatial arrangement of axial lines and the visual structure of space, in shaping individuals' navigation behavior. Moreover, the impact of spatial configuration on navigation performance appears to vary depending on task demands and the cognitive strategies employed by individuals. These strategies, in turn, are influenced by factors such as age [8]. This suggests that different age groups may be affected by spatial environments in distinct ways, which can significantly affect their navigation outcomes. These findings not only contribute to the development of more effective cognitive assessment methods but also offer valuable insights for designing age-friendly urban environments that promote safe, efficient, and accessible navigation.

Limitations and Future Work

This research highlights the critical role of cognitive abilities and spatial configuration in shaping navigation behavior. However, several limitations should be acknowledged. First, the participant sample may not fully represent the broader population. The younger participants were primarily between 20 and 30 years old, while the older group ranged from 65 to 85 years, leaving a substantial gap between ages 30 and 65 that was not included. This omission limits the generalizability of the findings, as individuals in this middle age range may exhibit distinct navigation patterns and cognitive characteristics that were not captured in the current analysis. Second, the scale of the VE may have been too constrained, potentially simplifying the complexity of real-world navigation and limiting opportunities for participants to display naturalistic wayfinding strategies. A more expansive and ecologically valid virtual setting might yield richer behavioural data and reveal additional nuances in navigational performance. Third, the study did not explicitly account for the influence of demographic factors such as gender, educational background, or geographic and cultural experience. Ignoring these variables could obscure important individual differences and interactions relevant to wayfinding performance.

Future research should aim to address these limitations by recruiting a more demographically diverse participant sample, including middle-aged individuals, and by employing larger, more complex VEs. Additionally, systematically examining the role of experiential factors could provide deeper insights into how individual and environmental characteristics jointly shape spatial navigation abilities in both virtual and real-world contexts. From a rehabilitation perspective, the findings suggest promising potential for virtual navigation tasks as a controlled and adaptable platform for personalized cognitive training, particularly in aging individuals or those with spatial memory deficits. Future research could investigate the incorporation of adaptive task difficulty and longitudinal monitoring into VR-based rehabilitation, thereby supporting the maintenance or recovery of spatial and cognitive functions.

Conclusions

This research not only reveals that the spatiotemporal features of virtual navigation games are shaped by both cognitive abilities and environmental structure, but also advances methods for more effective cognitive assessment. Additionally, areas with higher integration contribute to a more favorable navigation experience. However younger participants, or those with better cognitive abilities are more likely to prioritize traversing lower-integrated areas to enhance navigation efficiency, leading to more optimal navigation strategy.

Although still in the early stages of exploration, the proposed navigation game offers a promising foundation for the convenient and accurate detection of cognitive and navigational deficits. Furthermore, these insights may provide valuable guidance for the design of age-friendly urban environments that promote safe and efficient navigation, including the placement of landmarks and the design of signage systems, to better support the navigational needs of diverse populations.

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