Association between cognitive reserve and spatial ability across the lifespan

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Abstract

Spatial navigation is a promising cognitive marker for several cognitive disorders. However, its clinical utility is still limited because spatial abilities are also influenced by non-pathological factors. Among these, the Cognitive Reserve (CR) stands out due to its strong influence on cognitive aging trajectories. However, the association between CR and spatial navigation across the lifespan has never been assessed. In this study, we collected spatial navigation data along with CR measures in a population with diverse demographic profiles. We found a strong decline in spatial ability with age, but no overall effect of the CR. We systematically analyzed the association between each CR item and spatial ability and found that the subscore related to reading habits was significantly associated with spatial navigation performance, even after correcting for multiple comparisons. We discuss the implications of these findings for early and personalized screening for cognitive disorders using a spatial navigation task.

Keywords: Spatial navigation, cognitive reserve, cognitive aging, cognitive disorders, reading, demographics, personalized screening

Introduction

Difficulties in spatial navigation are among the earliest cognitive impairments observed in several cognitive disorders such as Alzheimer's disease (AD), making it a promising marker for early detection (Coughlan, Laczó, Hort, Minihane, & Hornberger, 2018). However, its diagnostic potential remains limited, as spatial abilities are also shaped by non-pathological factors such as age, gender, or socioeconomic factors (Coughlan et al., 2018; Coutrot et al., 2018). One key factor that may influence spatial navigation is cognitive reserve, which could contribute to differences in navigation strategies and resilience to age-related decline (Coughlan et al., 2018; Gilles et al., 2024). Cognitive reserve is an essential protective factor in aging, playing a key role in modulating the effects of brain lesions, neurodegenerative diseases, and normal aging on cognitive performance (Stern, 2009). Introduced in the 1980s, the concept of cognitive reserve is based on the idea that certain individual characteristics, such as education, life experiences, and intellectual engagement, enable the brain to better resist or compensate for pathological alterations (Stern, 2009).

Several studies have shown that people with high cognitive reserve recover more quickly after brain injuries or strokes (Nunnari, Bramanti, & Marino, 2014). Additionally, in people with AD, high cognitive reserve helps maintain normal cognitive functions longer despite the progression of the disease. However, once the compensation threshold is crossed, cognitive decline often accelerates due to the extent of brain damage (Pappalettera, Carrarini, Miraglia, Vecchio, & Rossini, 2024).

In the context of normal aging, cognitive reserve also helps preserve cognitive abilities (Stern, 2009), although this effect can vary across cognitive functions. Some studies suggest that people with greater cognitive reserve do not necessarily exhibit superior performance in all cognitive domains, such as memory, processing speed, or executive functions, compared to those with lower cognitive reserve (Lavrencic, Churches, & Keage, 2018). These discrepancies in findings raise several methodological and theoretical questions. One explanation lies in the diversity of approaches used to measure cognitive reserve (Nogueira, Gerardo, Santana, Simoes, & Freitas, 2022). Education is often used as a primary proxy due to its accessibility and empirical robustness. Education is indeed correlated with greater cognitive stimulation throughout life, which supports the development and maintenance of adaptive neural networks (Savarimuthu & Ponniah, 2024). However, this approach remains limited as it does not account for other crucial factors (Nogueira et al., 2022). Other studies uses brain-imaging (Davis, Dennis, Daselaar, Fleck, & Cabeza, 2008), incorporate additional indicators, such as professional activities, cognitively stimulating hobbies, or social interactions, as these dimensions also influence brain plasticity and the efficiency of compensatory mechanisms (Stern, 2009). However, the diversity of methodologies used to evaluate cognitive reserve leads to biases and difficulties in comparing studies (Nogueira et al., 2022). Furthermore, no standardized and widely accepted measure exists for quantifying cognitive reserve, complicating the interpretation of findings and limiting the reproducibility of research (Nogueira et al., 2022).

Previous studies on cognitive reserve suffer from another major issue: participants are often drawn from rather homogeneous populations in terms of demographics, resulting in samples that tend to be highly educated, and of higher socio-economical status (Henrich, Heine, & Norenzayan, 2010). This tends to reduce the variance associated with demographic variables, which in turn compromises the generalizability of the results..

In this study, we propose to assess the associations between a cognitive task and a wide range of factors involved in cognitive reserve across the lifespan. Participants were recruited among the visitors of the ”musée des Confluences”, one of the main museum in Lyon, France. This out-of-laboratory data collection allowed us to test participants with much more diverse sociodemographic backgrounds than if we had asked volunteers to be tested in our research facility. We chose spatial navigation as a proxy for cognition for two reasons. First, spatial navigation is a complex skill that engages multiple cognitive functions, including memory, attention, executive functions, and visuospatial abilities (McNamara, 2017). Second, spatial ability is one of the earliest cognitive function altered by AD, which makes it a particularly promising AD cognitive marker (Coughlan et al., 2018). Many demographic factors have been associated with spatial ability, such as age, gender or nationality (Spiers, Coutrot, & Hornberger, 2023), but cognitive reserve has never been directly investigated. Understanding how cognitive reserve is associated with spatial ability in normal and pathological ageing is key to help doctors to screen for pathological profiles with precision and personalization.

Methods

Participants

301 healthy participants were recruited between April 13 and April 28, 2024, among the visitors of the Musée des Confluences in Lyon. We had a booth in the main hall of the museum where the participants were informed about the experiment and could sign a consent form. Participants ranged in age from 18 to 82 years. Of these, 293 participants completed all the stages of the experiment. Three participants were excluded from statistical analyses because their spatial navigation performance exceeded three standard deviations below the mean, reducing the sample was reduced to 290 participants: 114 men, 173 women, and 3 identifying with another gender. The mean age was 41.1 years (SD = 16.6), including 47 participants aged between 60 and 82 years.
Participants educational background was distributed as follows: 3 participants had no formal diploma or only a primary or middle school certificate; 28 had a high school diploma or vocational qualification; 10 had a technical or trade certificate; 26 completed a two-year higher education program; 56 held a bachelor’s degree (at least three years of higher education); and 86 had a master’s degree or higher.
Regarding professional categories, 17 participants worked in unskilled jobs, such as laborers, gardeners, servers, drivers, or caregivers. 35 were skilled workers or artisans, including cooks, salespeople, nurses, or hairdressers. 43 participants held roles in commerce, real estate, religious vocations, or creative professions. 27 were high-ranking professionals, such as executives, university professors, doctors, or researchers. 86 participants were small business owners or professionals in qualified fields, including lawyers, engineers, or teachers. One participant was unemployed.
All participants were screened to ensure they were cognitively healthy, with no history of psychiatric, neurological, or cognitive disorders. They had normal or corrected-to-normal vision and no blindness or visual impairments that could compromise participation in the study. Participants were also required to have abstained from using substances that could influence cognitive performance.
The study was approved by the Research Ethics Committee of the University of Lyon on January 31, 2024 (reference no. 2024-01-11-001).

Cognitive Reserve Questionnaire

The Cognitive Reserve Questionnaire was adapted from the study by (Rami et al., 2011). This tool evaluates the degree of cognitive reserve in both healthy individuals and patients with early-stage AD. It was designed for simple and rapid assessment. The Questionnaire consists of 25 items designed to measure various aspects of cognitive reserve, including parental education, highest educational attainment, number of professional training courses completed, occupation, musical engagement, number of languages spoken, books read annually, and intellectual games (e.g., crosswords, chess) played monthly.

Spatial Navigation Task

Sea Hero Quest, launched in 2016 by researchers from University College London and the University of East Anglia (United Kingdom), is a video game aiming to quantify people's spatial navigation skills across the planet. With over four million players on smartphones and tablets, this game has provided a diverse sample of players based on demographic criteria such as country of residence, age, and gender (Spiers et al., 2023). However, no Cognitive Reserve measures have been collected. Participants' performances in Sea Hero Quest has been compared with a real-world ecological navigation task, revealing a significant correlation between virtual and real-life performances (Coutrot et al., 2019; Goodroe et al., 2025).

The video game focused on a specific spatial orientation task called "Wayfinding," which requires participants to engage in complex cognitive processes. These include interpreting a map, planning a multi-step route, memorizing the path, monitoring progress along the route, updating the navigation plan, and transforming an aerial map perspective into an egocentric viewpoint for real-time navigation.
During the task, participants were shown a map indicating the starting point and the locations of one to three checkpoints, see Figure 1. After viewing the map, they began the task without further access to it. They were required to navigate through a virtual environment to visit the checkpoints in the correct order as quickly as possible. To minimize the effect of familiarity with video games or smartphones, Sea Hero Quest was designed to be very simple to handle. Participants just had to tap on the left (resp. right) of the screen to turn left (resp. right). To familiarize participants with the task, Levels 1 and 2 served as tutorial and training levels. These levels were analyzed separately to measure familiarity with smartphones and video games, and to distinguish motor skills from true spatial navigation abilities. The task was completed on a Fairphone 5, equipped with a 6.46-inch OLED display, a resolution of 2700 x 1224 pixels, and a 90 Hz refresh rate.

Spatial Ability Metric

We collected each participant's trajectory across levels 1, 2, 6, 8, 11, and 23. We chose these levels to quantify spatial behavior in various environments while limiting the task difficulty. More advanced levels can be quite challenging and lead to a ceiling effect, in particular for older participants. The coordinates of the participants' trajectories were sampled every 500 ms. As in previous studies (Coutrot et al., 2018, 2022), we computed the trajectory length in pixels, defined as the sum of

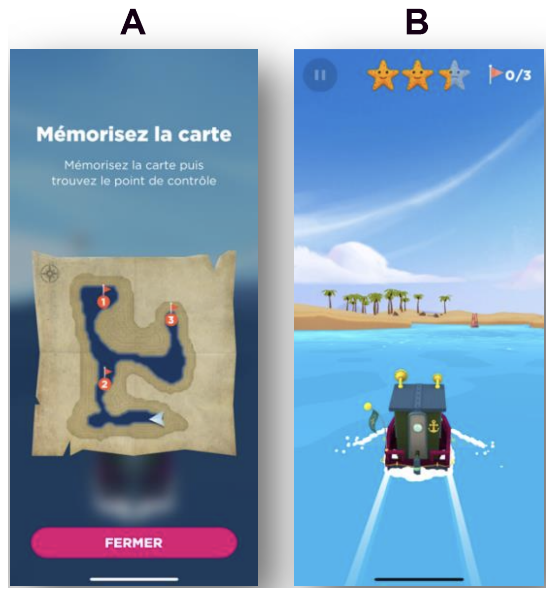

Figure 1: Navigation map of level 11 (A) from the video game Sea Hero Quest, along with an in game screenshot of the same level (B). In the map, the arrow in the bottom-right corner corresponds to the inital position of the boat, and the flagged numbers correpond to the checkpoints to reach in a set order. Once the participant hits the CLOSE button ("FERMER" in French), the map disappears and the wayfinding phase begins.

the Euclidean distances between the points of the trajectory. For each level, we took the z-score of the participant's trajectory length. This normalization leads to more interpretable results across levels, which can have different sizes. We defined the wayfinding trajectory length metric as the average between the z-scored trajectory lengths of wayfinding levels 6, 8, 11, and 23. Because this metric is based on the trajectory length, it varies as the inverse of the performance: the longer the trajectory length, the worse the performance.

Results

The objective of this analysis was to examine how Cognitive Reserve and its individual subcategories, as measured by the Cognitive Reserve Questionnaire, influence performance on a spatial navigation task. We conducted our analysis on two groups of participants. For the global cognitive reserve score, students were excluded since they were unable to answer questions related to their profession and or their number of professional trainings, resulting with 209 participants. This sample included 87 men, 121 women, and 1 participant of another gender, with a mean age of 47.44 years (SD = 14.82).
Additionally, we conducted a separate analysis focusing on specific subcategories of cognitive reserve that students could respond to, such as reading habits, musical activities, languages spoken, intellectual games, parental education, and highest diploma obtained. For this analysis, all 290 participants were included, comprising 114 men and 173 women

Table 1: Linear regression model predicting wayfinding trajectory length age, cognitive reserve (CR) and their interaction.

Variable	Coeff	SE	p-value
Intercept	-0.749	0.385	0.053
Age	0.018	0.008	0.022
CR	-0.043	0.030	0.158
Age × CR	0.001	0.001	0.108

and 3 from an other gender, with a mean age of 41,1 years (SD = 16.6). For the profession and or the number of professional trainings subcategory we conducted the analysis with the sample excluding the students (n=209).

In order to measure familiarity with smartphones and video games, and to distinguish motor skills from true spatial navigation abilities we calculated Pearson's correlation coefficient of trajectory lengths in Wayfinding levels and in Training levels for all participants (n = 290). The correlation between age and training levels was r(288) = .24, $p < .001$, whereas the correlation between age and orientation level performance was r(288) = .66, $p < .001$. Additionally, a formal comparison of these two correlations was conducted using the R function cocor (Diedenhofen & Musch, 2015). Zou's (2007) test revealed that the 95% confidence interval for the difference between these correlations was [.31, .53], rejecting the null hypothesis since the lower bound of the interval was greater than zero. This indicates that the correlation between age and orientation level performance is significantly stronger than the correlation between age and training levels.

We performed a multiple linear regression analysis with wayfinding trajectory length as the dependent variable and age, global cognitive reserve score and their interaction as the independent variables. The model revealed a non significant relationship between cognitive reserve score and wayfinding trajectory length (p = 0.16) see Table 1. Age was a statistically significant predictor of wayfinding trajectory length, with an estimate of 0.018 (SE = 0.008, p = 0.022), indicating that as age increases, the trajectory length increases as well. The interaction term between age and cognitive reserve was not statistically significant (p = 0.11). We obtained comparable results for participants aged over 60, with a significant effect of age (t = 2.132, p = 0.04) and no significant effect of cognitive reserve (t = 0.71, p = 0.48). We further explored the relation between subcategories of the Cognitive Reserve Questionnaire and spatial navigation performances using the Least Absolute Shrinkage and Selection Operator (LASSO) regression (Tibshirani, 1996). This regularization technique penalizes less significant predictors, producing a more parsimonious and interpretable model. LASSO identifies the most relevant predictors by showing only the variables with substantial contributions to the outcome.

The LASSO regression qualitatively revealed that reading habits and engagement in intellectual games were positively

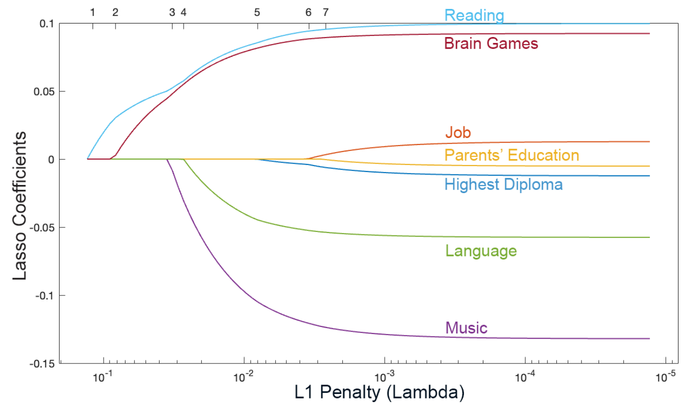

Figure 2: Trace Plot of Coefficients Fit by Lasso. The outcome variable is the z-scored wayfinding trajectory length, the predictors are the Cognitive Reserve items. LASSO is similar to standard regression, but the L1 penalty penalises the number of predictors: the higher the penalty, the sparser the model (left-hand side of the plot).

associated with wayfinding trajectory length, see Figure 2. This indicates that higher scores in these subcategories were linked to poorer performance on the navigation task. Conversely, music involvement and the number of languages spoken were negatively associated with wayfinding trajectory length, suggesting that participants scoring higher in these dimensions exhibited better navigation abilities. Parental education, highest degree obtained, professional training, or occupation were very weakly associated with navigation performance.

We then quantitatively tested each subcategory of the Cognitive Reserve Questionnaire using a multiple linear regression predicting wayfinding trajectory length with age, the subcategory item and their interaction. We calculated partial Eta Squared (η^2) to measure the effect size of each cognitive reserve subcategory on spatial navigation performance. To account for multiple comparisons, we adjusted the significance threshold using Bonferroni correction by dividing the original alpha threshold (0.05) by the number of tests performed (0.05/8), resulting in a new alpha threshold of 0.006. The reading score was the only item significantly associated with navigation performance (η^2=0.01, p = 0.003), see Table 2. As shown in Table 3, the interaction between age and reading ($\beta = 0.005$, $p < .001$) is strongly significant. Since this interaction is positive, the simple regression coefficients for age and reading alone cannot be interpreted in isolation, as their effects vary depending on each other. This suggests that for younger participants, reading has less impact on spatial navigation performance than for older participants. This interaction is clearly shown in the boxplots in Figure 3, where we plotted the reading scores as a function of wayfinding trajectory length for participants aged 40 and older (upper panel) and for participants under 40 years

Table 2: For each item of the Cognitive Reserve Questionnaire (CRQ), a linear regression model predicting wayfinding trajectory length with age, the CRQ item and their interaction.

Subcategories	Partial η^2	p-value
Parent's education	0.014	0.55
Highest diploma	0.010	0.35
Professional training	0.013	0.206
Occupations	0.001	0.099
Music	0.003	0.15
Language	< 0.001	0.94
Reading	0.1	0.003 **
Intellectual games	0.003	0.24

Table 3: Linear regression model predicting wayfinding trajectory length with age, reading and their interaction.

Predictor	Coeff	SE	p-val	Partial η^2
Intercept	-0.739	-6.42	$< .001$	-
Age	0.013	3.75	$< .001$	0.309
Reading	-0.161	-2.95	.003	0.010
Age × Reading	0.005	0.001	$< .001$	0.054

Note. Adjusted R^2 = 0.476, $F(3, 289)$ = 89.47, p $< .001$.

old (lower panel). The figure suggests that the association between higher reading scores and poorer spatial navigation performance becomes more pronounced with age. We ran the same linear regressions as above on these two independent subgroups and found that the effect size of reading habits on spatial ability is η^2=0.077 in the older group and only η^2=0.001 in the younger group.

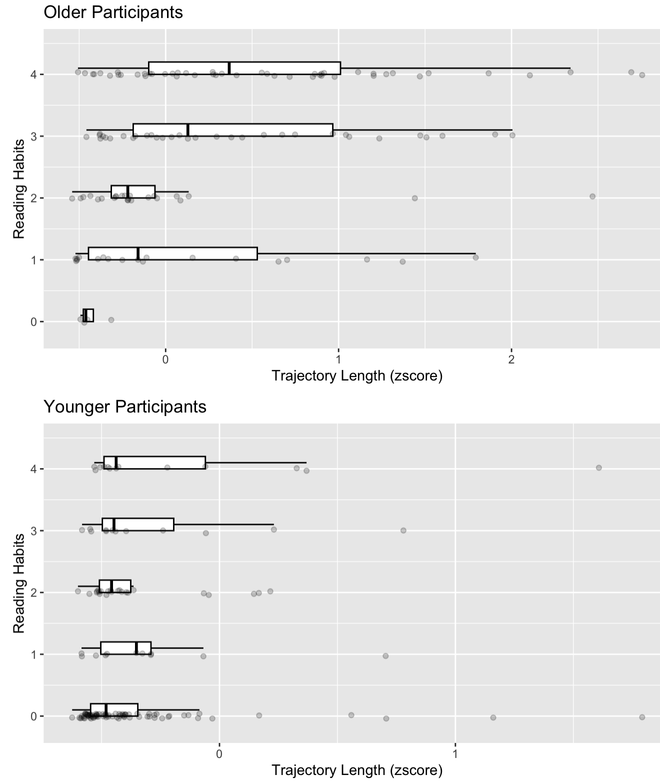

Figure 3: Reading habit as a function of spatial trajectory length for younger ($<$ 40 y.o., top) and older ($>$ 40 y.o., bottom) participants. Reading habits are quantified in 5 categories: Never (0), Occasionaly (1), 2 to 5 books/year (2), 5 to 10 books/year (3) and $>$ 10 books/year (4). In the boxplots, the horizontal bar represents the sample median, the hinges represent the first and third quartiles, and the whiskers extend from the hinges to the largest/lowest value no further than ±1.5 * IQR from the hinge (where IQR is the inter-quartile range).

Discussion

This study investigated the relationship between cognitive reserve and spatial navigation performance across the lifespan. This research question is particularly interesting since spatial ability is a promising cognitive marker for the early screening of several cognitive disorders (Coughlan et al., 2018). To provide a more personalized and reliable assessment, we hypothesized that cognitive reserve would be an important non-pathological factor to control for. Indeed, cognitive reserve is an essential protective factor in both pathological and normal aging (Stern, 2009). The relationship between cognitive reserve and spatial navigation across the lifespan has never been directly tested. To fill this gap, we collected spatial navigation data and detailed demographics from participants recruited at a museum. This gave us access to a more diverse sample in terms of demographics than in classical lab-based experiment. Our results show a decline in spatial navigation with age, consistent with the scientific literature (Zhong & Moffat, 2016; Coutrot et al., 2018). The correlation between spatial ability and the cognitive reserve score was non-significant, and so was its interaction with age. Regarding the subcategories of the Cognitive Reserve Questionnaire, the LASSO regression analysis revealed that higher engagement in reading and intellectual games was positively associated with longer spatial trajectories, indicating poorer navigation performance. In contrast, involvement in music and the number of languages spoken were negatively associated with trajectory length, suggesting that participants with higher scores in these domains exhibited superior navigation abilities. Other cognitive reserve factors, such as parental education, highest degree obtained, and professional training, showed weak associations with navigation performance.

We then tested the association between spatial ability and each subcategory of cognitive reserve while controlling for age, and computed the corresponding effect sizes. Overall, the effect size of reading (∼1% of the variance) was relatively small compared to the stronger influence of age (∼31% of the variance) on navigation performance, but it is reinforced in older participants, reaching ∼7.7% above 40 years old.

One possible explanation for this significant negative association between reading habits and navigation performance lies in the cognitive processes required for each task. Reading is primarily a symbolic and verbal activity, which involves processing information in a linear and sequential manner (Conway & Pisoni, 2008). In contrast, spatial navigation is a visuo-spatial task that demands the ability to mentally represent and orient oneself within space (McNamara, 2017). Our analysis suggests that participants with higher reading scores may rely more on verbal or symbolic strategies for navigation, rather than utilizing the visuo-spatial strategies typically employed in navigation tasks (Reichle, Carpenter, & Just, 2000). For example, individuals might memorize routes through detailed verbal descriptions or associations with landmarks, rather than creating detailed mental maps of the environment. This divergence in cognitive strategies is consistent with findings from other studies exploring the interplay between verbal and spatial strategies in navigation. The study from Kraemer et al. (2017) investigated how verbal and visual strategies influence navigation in a virtual environment. The authors found that participants who preferred verbal strategies performed worse in tasks requiring direction judgment, suggesting that verbal strategies may be less effective for certain navigation tasks. This aligns with our finding that participants with stronger reading skills, who likely rely more on verbal encoding, exhibited longer spatial trajectories. Their preference for verbal strategies could have hindered their ability to quickly adapt to and navigate spatial environments, particularly in novel or complex settings.

Another essential outcome came from the strong interaction between reading habits and age. One possible explanation for this difference in reading effect size across the lifespan is that individual differences in verbal and spatial working memory are linked to cognitive flexibility and the ability to switch between verbal and spatial resources effectivelyn (Bacon, Handley, Dennis, & Newstead, 2008). This suggests that younger people are more adept at switching cognitive strategies, while older adults face difficulties due to a decline in cognitive flexibility, which makes it more difficult to adapt to different tasks (Bacon et al., 2008).

Aside form reading skills, the role of practical experience in spatial navigation cannot be overlooked. Previous studies, such as the work by Fernandez-Velasco & Spiers (2024) on London taxi drivers, have demonstrated that experience and regular exposure to complex environments can significantly improve spatial navigation skills. Taxi drivers, who acquired an in-depth knowledge of the city's layout through daily practice, exhibited superior navigation abilities compared to the general population. In our study, it is possible that participants with higher reading scores have more sedentary lifestyles, limiting their exposure to environments that require their navigation skills. While reading may contribute to cognitive reserve, it may not provide the same kind of real-world spatial experiences that enhance navigation abilities.

Strengths and Limitations of the Study

The strengths of this study primarily lie in the large sample size of healthy participants and their wide distribution of ages. Furthermore, the measurement of spatial navigation performance through a video game was controlled to prevent familiarity with video games from influencing the results.

Recruiting participants outside the laboratory has its advantages, as laboratory studies are often subject to selection biases since participants must choose to attend, which frequently leads to an over representation of certain profiles (Henrich et al., 2010). However, it is important to note that museum visitors tend to belong to a specific socio-demographic profile, which may limit the representativeness of our sample in relation to the general population (Falk & Dierking, 2018).

It should also be mentioned that the questionnaire we used to assess cognitive reserve is not universally accepted in the scientific community. To date, there is no quick and easy-to-use questionnaire that is universally validated by researchers. Additionally, in the context of our research, the questionnaire may not capture all the relevant dimensions of cognitive reserve, particularly in the specific context of spatial navigation. Measures such as participants' professions may not fully represent their actual cognitive abilities. The attribution of scores based on professions could be subject to discussion. To improve the assessment of cognitive reserve, it would be beneficial to adopt more specific and detailed measures that take into account the diversity of professional experiences and intellectual activities. Clarification of professional training criteria would allow for better data collection.

Conclusion and Perspectives

Our hypothesis that the cognitive reserve slows down the age-related cognitive decline measured with a spatial navigation task was not confirmed. However, as we age, the number of book read was negatively correlated to navigation performances. These findings underscore the complexity and interplay of factors influencing spatial navigation and call for further research to better understand these relationships. Identifying the most important factors will allow to refine the comparison of spatial behavior between patients and controls sharing a similar socio-demographic profile, leading to a personalized cognitive screening for cognitive disorders such as Alzheimer's disease.

Code and Data availability

The code and data necessary to reproduce the results presented in this manuscript are available on Open Science Framework: `https://osf.io/8am5u/?view_only=ecc458370c7a4903948fd5fd7da8b6b1`

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