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The effect of aging on spatial navigation

A characterisation of navigational ability in the elderly

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Abstract

Spatial navigation is a highly complex cognitive ability necessary for everyday functioning. Like most cognitive abilities, spatial navigation is affected by age. Nevertheless, more research is necessary to understand the full effects of age on navigation behaviour. In order to provide a detailed characterisation of navigation behaviour in the elderly, this study utilised a recently developed functional model of navigation behaviour.

The quality of landmark knowledge (LK), the egocentric frame of reference (EFoR), the allocentric frame of reference (AFoR), route knowledge (RK) and survey knowledge (SK) was measured in healthy participants ($N = 2591$) using an online navigation experiment. The achieved scores were calculated for each of the five aforementioned aspects of navigation behaviour. These scores were then used to create a visual representation of aging for each of the aspects. In addition, two MANOVA's were used to determine if and when the aspects started to substantially deteriorate.

The results showed that each of the five measured aspects of navigation behaviour was affected by age. When compared to the reference group, which consisted of 18- to 25-year-olds, LK was shown to substantially deteriorate between the ages of 46 and 51, $p < .01$. Furthermore, the EFoR and RK showed a similar pattern of aging: both remained intact until the age of 51. Then, between the ages of 51 and 55, the quality of these aspects started to deteriorate, $p < .01$ and $p < .01$. Moreover, the quality of the AFoR declined the earliest, namely between the ages of 41 and 45 years, $p < .01$. Lastly, SK deteriorated the latest and remained intact until the age of 69 years, $p < .025$.

This study could be useful in (early) diagnostics of neurodegenerative diseases and helpful in developing rehabilitation programmes for impairments in navigation.

Introduction

Spatial navigation is a fundamental, yet highly complex cognitive ability necessary for everyday functioning. What makes it complex, is that spatial navigation is the result of the interaction between multiple cognitive mechanisms. For one to adequately find their way from one location to another, the brain has to integrate input from various sensory modalities, such as the visual and proprioceptive systems (Berthoz &Viaud-Delmon, 1999). Next, spatial representations are created in short-term memory and then maintained in long-term memory. These representations are then used to influence navigation behaviour (Wolbers & Hegarty, 2010).

Until recently, the literature on navigation behaviour lacked an adequate functional model of navigation. The development of a functional model is not only important for understanding navigation behaviour in healthy individuals, it can also be used to categorize impairments in navigation behaviour. Claessen and van der Ham (2017) developed such a model by systematically reviewing neuropsychological case studies. This model states that spatial navigation comprises three types of representations, concerning landmarks, locations, and paths.

First of all, navigation requires knowledge of landmarks. This type of knowledge is also known as landmark knowledge (LK). Landmarks are salient elements in an environment which can be used as points of recognition.

Second, knowledge of locations includes the locations of landmarks and how these places relate to each other. There are two frames of reference in which spatial information can be stored. An egocentric frame of reference (EFoR) uses the self as the centre in the organization of spatial information (Roskos-Ewoldsen, McNamara, Shelton, & Carr, 1998). In contrast, an allocentric frame of reference (AFoR) is centred on the environment. It uses information about landmarks, for example distances, in the environment independent of the self (McNamara, 2002).

Finally, knowledge of paths is required. This kind of knowledge consists of paths that connect locations with each other**.** Path knowledge can be represented in two different ways. Route knowledge (RK) is an egocentric representation of a path. Landmarks are thus located by referring to one’s own position (Montello, 1998). Survey knowledge (SK) is a map-like or allocentric representation of a path. It can basically be defined as topographic knowledge of specific environments (O’keefe & Nadel, 1978; Boccia, Guariglia, Sabatini, & Nemmi, 2016).

The model developed by Claessen and van der Ham (2017) may be able to shed some light on certain pressing issues regarding navigation behaviour, since existing studies seldom make use of such a model. The model could, for instance, be of help in clarifying the effect of physiological aging on navigation behaviour. Physiological aging comes with many functional and structural changes in the brain, which start to occur from the age of 40 (Peters, 2006). Most pronounced are reductions in the volume of the prefrontal cortex (Resnick, Pham, Kraut, Zonderman, & Davatzikos, 2003) and the hippocampus (Grady, McIntosh, Rajah, Beig & Craik, 1999). Reduction in the volumes of these structures are associated with a general decline in executive and attentional functions (Iachini, Iavarone, Senese, Ruotolo, & Ruggiero, 2009). In addition, the frontal and parietal lobes are found to be especially vulnerable to grey matter loss (Resnick et al. 2003). However, it is not yet fully known in what way these structural and functional changes affect navigation behaviour.

As to LK, older adults acquire less environmental knowledge than younger adults. That is to say, aging is associated with lower recall of landmarks one encounters in the environment. This deficiency in landmark recall likely contributes to the problems elderly people experience in spatial navigation (Head & Isom, 2010).

With regard to knowledge of locations, elderly people experience difficulties in the usage of the AFoR, as well as the EFoR. There is evidence that older adults experience difficulties using allocentric strategies in spatial tasks (Iaria, Palermo, Committeri, & Barton, 2009; Jansen, Schmelter, & Heil, 2010). Jansen et al. (2010), for example, designed a virtual environment in which a navigational task had to be solved. The navigational task assessed the formation and use of an allocentric representation of the environment. The results showed that it took older adults longer to form an allocentric representation than younger adults. Furthermore, in comparison to young adults, older adults show poorer allocentric performance in memorizing unfamiliar environments (Wilkniss, Jones, Korol, Gold, & Manning, 1997). The following may be a possible explanation. Moffat, Elkins and Resnick (2006) suggest that reduced activation in the posterior hippocampus and parahippocampal gyrus are responsible for difficulties in allocentric processing in elderly people. Both these areas are believed to play a role in allocentric processing (O'Keefe & Nadel, 1978). The reduced activation of these areas might contribute to the slower formation and less accurate usage of cognitive maps in older adults (Iaria et al., 2009). The slower formation of cognitive maps may lead to a shift from a predominant allocentric strategy to an egocentric strategy (Ruggiero, D'Errico, & Iachini, 2016).

Even though a shift to an egocentric strategy might occur, older adults also showed difficulty in spatial tasks requiring egocentric encoding (Wilkniss et al., 1997). In addition, Ruggiero et al. (2016) conducted an egocentric judgement task among participants aged 8 to 89. Older adults performed less accurate than young adults. More precisely, the results showed that the egocentric ability started to decrease from the age of approximately 60 years. This decrease continued progressively and resulted in a distinct drop during the eighties. With regard to neural correlates, the EFoR seems to particularly rely on a fronto-parietal network along the dorsal stream (Committeri et al., 2004).

RK was found to recruit a occipito-fronto-parieto-temporal network. Additionally, RK is associated with activity in the associated structures of this network, which are the hippocampus, parahippocampal gyrus (bilateral), insula and caudate nucleus (Latini-Corazzini et al., 2010). Furthermore, Hartmeyer, Grzeschik, Wolbers and Wiener (2017) showed that older adults responded slower and were slower in route learning. The slower responses, however, could be attributed to aging-related declines in information processing speed.

Similar to RK, SK was found to be dependent on structures related to the occipito-fronto-parieto-temporal network, with exception of the caudate nucleus. In addition, the parahippocampal gyrus showed heightened activity, but only in the right hemisphere (Latini-Corazzini et al, 2010). Moreover, Iaria et al. (2009) conducted an experiment concerning the use of SK. Participants were instructed to create a mental representation of a virtual environment and the six landmarks it contained (i.e. an allocentric representation of the environment), as they would need this mental representation in the next task. After freely roaming the environment, participants started at one of the landmarks and were instructed to reach a target location (i.e. one of the other five landmarks) as quickly as possible. Results showed that older adults were less efficient in using cognitive maps for the purpose of orientation in comparison to young adults. In essence, older adults were less efficient in using their SK. Head and Isom (2010) conducted a similar experiment, which yielded a similar outcome.

The main purpose of this study is to provide a characterisation of navigation behaviour in the elderly, using a functional model of navigation. This characterisation has various purposes. First, in the current available literature, the effect of physiological aging on navigation behaviour is described by comparing the performances of age groups with limited age ranges (Hartmeyer et al., 2017; Head & Isom, 2010; Iaria et al., 2009; Wilkniss et al., 1997). Therefore, it is unknown exactly when the different aspects of navigation behaviour start to decline.

Additionally, it might be useful for the early detection of neurodegenerative diseases, such as Alzheimer's disease. Getting lost in familiar environments is often present in the early stages of the disease, sometimes even before impairments in verbal memory (Klein et al., 1999). Hort et al. (2007) compared healthy elderly people, people diagnosed with Alzheimer's disease and people diagnosed with mild cognitive impairment[1] on an allocentric encoding task. Results showed that allocentric encoding was impaired in people diagnosed with Alzheimer's disease or mild cognitive impairment. Altogether, impaired allocentric processing might be a prodromal symptom of, among others, Alzheimer's disease. So, if a regular pattern of aging is established, any deviation from this pattern can be interpreted in a clinical context and thus be used in (early) diagnostics.

In a similar way, a characterisation of navigational ability in the elderly might be useful in the development of rehabilitation programmes for navigation impairment. Navigation behaviour is extremely vulnerable to brain damage, as the cognitive nature of this function is quite complex (Ruggiero, Frassinetti, Iavarone, & Iachini, 2014). Even though navigation impairment is a common complaint after acquiring brain injury, the amount of rehabilitation programmes focussed on improvement of navigation behaviour is limited (Claessen, van der Ham, Jagersma, & Visser-Meily, 2016).

According to the reviewed literature, there should be an age-related decline in the performance on all aspects of navigation behaviour. More specifically, the usage of an EFor is expected to decline from the age of 60. From the age of 80 a clear drop may be observed (Ruggiero et al., 2016). Furthermore, LK (Head & Isom, 2010) and the usage of an AFoR (Iaria et al., 2009; Jansen et al., 2010; Ruggiero et al., 2016) are expected to decline between the age of 55 and 60. Moreover, RK will probably decline from the age of 60, similar to the EFoR. Last, SK may deteriorate as early as the age of 50 years (Iaria et al., 2009; Head & Isom, 2010). These ages are based on the age ranges of the older adult groups in the relevant literature.

[1] Mild cognitive impairment is a cognitive stage between normal aging and dementia

Methods

Participants

A total of 2591 participants, 934 males and 1648 females, were included in the statistical analyses. All participants included in this study were aged 18 years or older. In Table 1 demographic figures are provided. Before they were able to proceed to the experiment, participants had to declare whether they were of age, were free from any history of brain injury and psychiatric or neurological illnesses and had access to a stable internet connection. Participants aged younger than 18 years and participants who did not complete the full experiment were excluded from statistical analyses.

All participants gave informed consent to participate in this study. In the case of minors' participation, informed consent was also given by a parent or primary caretaker. Participants' recruitment and testing was approved by the local Ethics Committee.

Table 1. *Characteristics of the participants (n=2591)*

Age group	**Group size**	**Gender (percentage)**		**Education Level,**
		Male	**Female**	**mean (SD)***
18 – 25	530	137 (25.8)	390 (73.6)	6.5 (.6)
26 – 40	596	202 (33.9)	392 (65.8)	6.4 (.8)
41 – 55	714	222 (31.1)	490 (68.6)	6.1 (.7)
56 – 100	751	373 (49.7)	376 (50.1)	6.0 (.8)

Note: * The education levels are based on the classification system of Verhage (1964). Scores can range from 1 (lowest level of education: non-finished primary level of education) to 7 (highest level of education: finished university level of education).

Measures

First, participants had to give informed consent. Then they were asked to answer some demographic questions and questions that measure the subjective navigation ability.

The participants were informed about the fact that they were not allowed to have any history of psychiatric or neurological illnesses and brain injury in order for them to participate. Additionally, they were informed about the ethics involved in the experiment (their data was collected anonymously and is going to be used for scientific publication). Subsequently, participants had to agree that they had read and understood the text and that they would participate in the experiment under the stated condition (and thus gave informed consent).

After reading the conditions and giving informed consent, participants were presented with demographic questions regarding age (18 years of age or older), gender (male, female or other), educational level (basisonderwijs/lagere school, LBO, VMBO, MBO, HAVO, HBO, VWO, WO), living environment (rural or urban), the province where their hometown is located (Drenthe, Flevoland, Friesland, Gelderland, Groningen, Limburg, Noord-Brabant, Noord-Holland, Overijssel, Utrecht, Zeeland, Zuid-Holland or 'I don't live in the Netherlands') and spatial expertise (participants were asked how frequent they travel to places they have not been before. They could select one of the following answers: never, multiple times a year, multiple times a month, on a weekly basis or more often.)

Last, participants were presented with the following three questions selected from the Wayfinding Questionnaire (Claessen, Visser-Meily, de Rooij, Postma & van der Ham, 2016): 'I can usually recall a new route after I have walked it once.', 'I am afraid to get lost in an unknown city.' and 'I can estimate well how long it will take me to walk a route in an unknown city when I see the route on a map (with a legend and scale).'. These questions can be used to measure three aspects of the subjective navigation ability, that is to say sense of direction, spatial anxiety and distance estimation respectively. The participants were asked to answer the questions on a scale of one (not at all applicable to me) to seven (fully applicable to me). These specific questions covered the three aspects of subjective navigation ability best.

When the participants completed the questionnaire, the navigation game began. Participants were told that their spaceship crashed on an undiscovered planet and that their goal was to find that very ship. Then they were shown a video of a route taken on this planet that led to the spaceship and were instructed to memorize what they saw. After they finished watching the video, five tasks had to be completed. Each task assessed separate aspects of navigation ability, based on the model provided by Claessen & van der Ham (2017).

The Landmark Identification Task measured the use of landmarks in one's navigation behaviour. Participants were presented with eight images (items) of landmarks that were (targets) and were not (distractors) part of the virtual environment. The participants subsequently had to indicate whether or not they saw these landmarks in the video. Participants could indicate they saw a landmark by selecting a green check mark. Similarly, participants could indicate they did not see a landmark by selecting a red cross as is depicted in Figure 1. If done so correctly throughout the task, participants could attain a maximum of 8 correct answers.

Furthermore, two trials of this task were available. Both trials consisted of different items. The assignment of the trials was randomized among the participants. Also, in both trials the order in which the items were presented, was randomized.

Figure 1. an example of the presentation of the items in the Landmark Identification Task.

In the Direction Indication Task, egocentric location memory was measured. Participants were asked to indicate in which direction the crashed spaceship was located as seen from the landmark they were subsequently presented with. Each item had 6 possible answers. Each possible answer was an image of the same landmark encountered in the video, however, every image contained an arrow pointing in a different direction, as shown in Figure 2. All participants were presented with 4 items, randomly selected out of 8 items. Thus, the score on this task could range from 0 to 4.

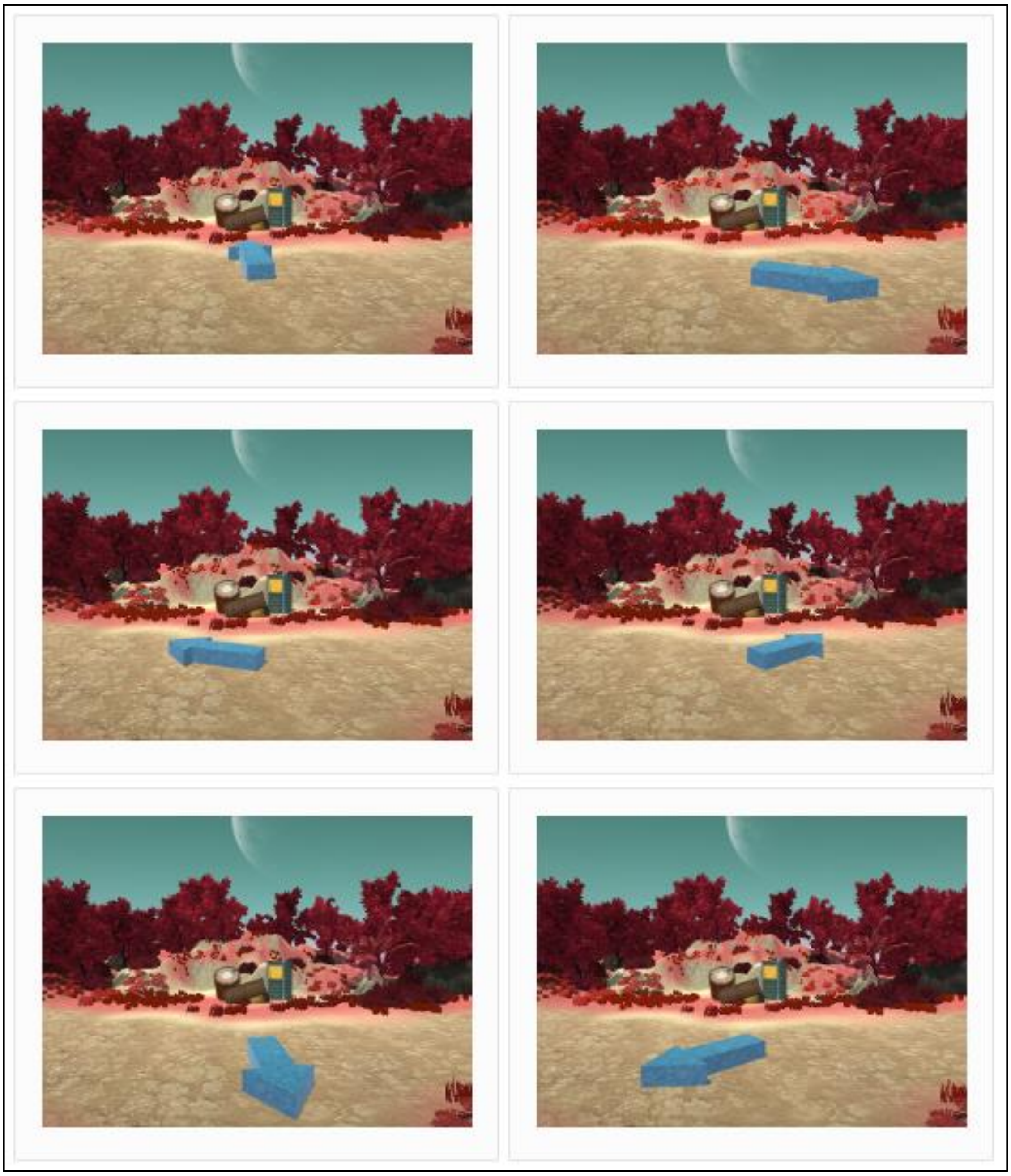

*Figure 2***.** an example of the presentation of the items in the Direction Indication Task.

Allocentric location memory was measured in the Landmark Location Task. Participants were instructed that they would be presented with a landmark they encountered in the video and a map of the environment. Thereafter, participants had to indicate where they encountered the landmark by selecting one of four possible locations on the map. The four possible locations were marked as A, B, C and D, as depicted in Figure 3. All participants were presented with 4 items, randomly selected out of 8 items. Thus, the score on this task could range from 0 to 4.

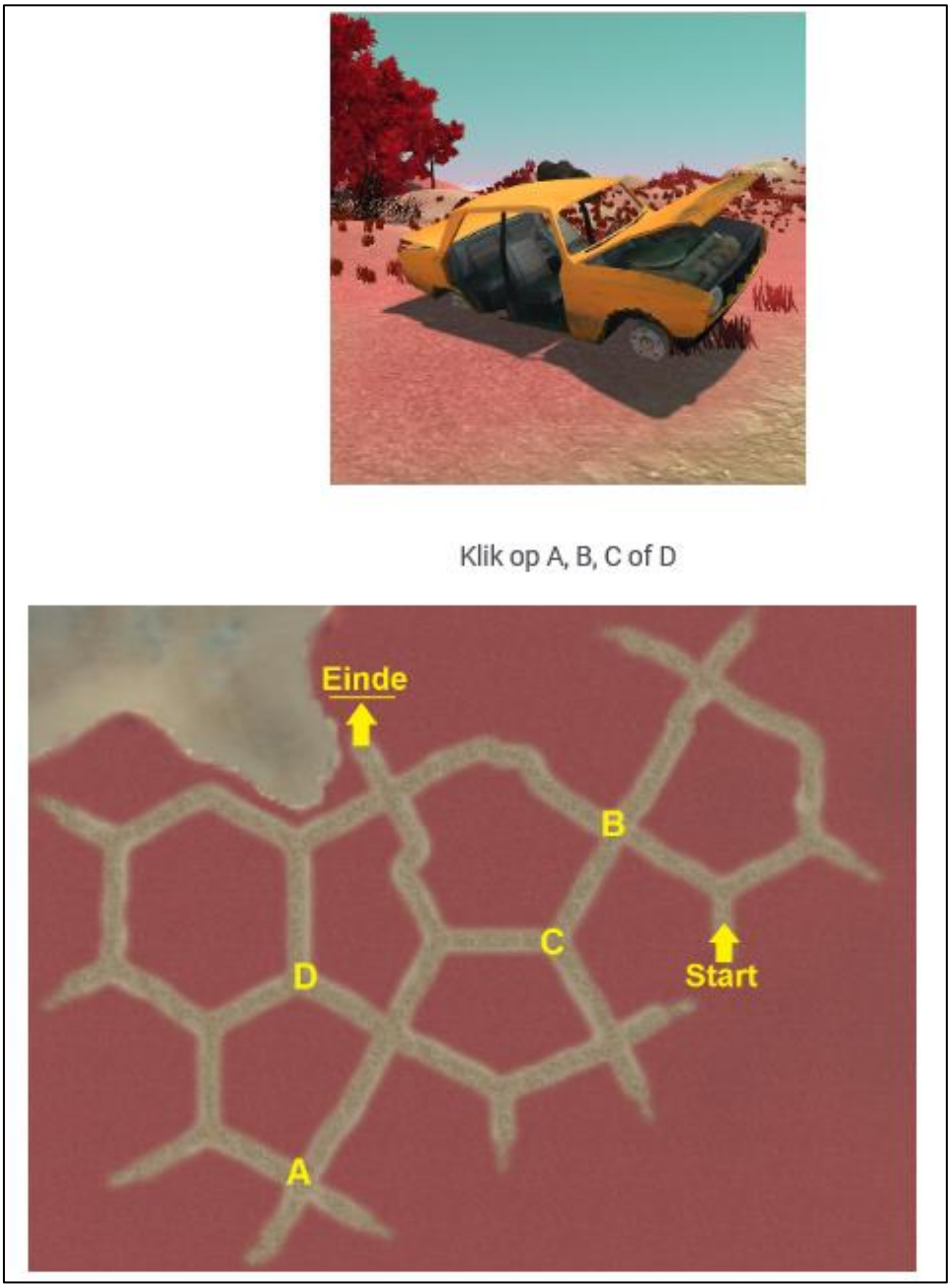

Figure 3. An example of the presentation of the items in the Landmark Location Task.

In the Route Continuation Task, the usage of RK was measured. In this task, participants were presented with an intersection they encountered in the video. Then, the participants had to indicate how the route continued from this point. Participants could indicate this by selecting the arrow corresponding to the direction they thought was correct, as shown in Figure 4. All participants were presented with 4 items, randomly selected out of 8 items. 5 out of 8 items were classified as easy, as there were only two answers possible on these items. The remainder of the items were classified as hard, as there were three answers possible on these items. The score on this task could range from 0 to 4.

Figure 4. An example of the presentation of the items in the Route Continuation Task.

Finally, the Proximity Task measured the use of SK. Participants were presented with three landmarks they encountered in the video, as depicted in Figure 5. Participants had to select the two landmarks that laid closest together. All participants were presented with 4 items. Thus, the score on this task could range from 0 to 4.

Figure 5. An example of the presentation of the items in the Proximity Task.

The tasks were presented in a randomized order, except for the Landmark Identification Task. The content of the other tasks could have given away the answers to the questions asked in the Landmark Identification Task if it was not presented first.

Participants were given the option to complete the remainder of the questions from the Wayfinding Questionnaire (Van der Ham et al., 2013). However, this part was not obligatory. Both these questions and the questions answered before the experiment began, were not used in the current study.

Design

The current study was a cross-sectional study. It was an online study, available for everyone from the age of eight years old. Each participant performed the same set of tasks without any manipulation whatsoever.

Potential participants were able to participate out of own initiative through the website 'www.navigerenkunjeleren.nl' or were actively asked to participate at the NEMO science museum throughout the 'Weekend van de Wetenschap' or the 'Museum Nacht'. The content of the experiment was the same for both conditions.

Statistical analyses

First, the quality of the usage of landmarks, RK, SK, AFoR and EFoR were calculated. For LK, the total amount of correctly identified targets and distractors on the landmark identification task was considered to be an accurate reflection of one's quality on this aspect of navigation behaviour. Similarly, the total amount of correct answers on the route continuation task and proximity task reflect the quality of the usage of RK and SK respectively. Furthermore, the quality of the usage of AFoR was calculated by adding the summed correct answers of both the proximity task and the landmark location task. The quality of the usage of the EFoR was calculated by adding the summed correct answers of both the route continuation task and the direction indication task.

Then, the scores on these variables were standardized by calculating the z-scores for these variables. The z-scores were calculated by saving the standardized values as variables using the descriptives option in SPSS.

Before any kind of analysis was performed, three assumptions were checked. First of all, there had to be multivariate normality. This was checked using the Kolmogorov-Smirnov test of normality. Second, there had to be homogeneity of variance-covariance matrices. This was checked with the Box's M Test of Equality of Covariance Matrices. Furthermore, homogeneity of error variances was checked by running Levene’s Test of Equality of Error Variances.

Then, a MANOVA (MANOVA 1) was performed to verify whether or not there were any significant differences between the scores on each task across age. The participants were divided into four different groups based on age as follows: 18 – 25 (young adults), 26 – 40 (adults), 41 – 55 (middle aged adults), and 56 - > 69 (old adults). Participants older than 69 years of age were assigned to one group, since these ages were less represented in the data. The independent variable was age groups and the dependent variables were the standardized scores on each of the representations (AFoR, EFoR, LK, RK and SK). A Games-Howell post hoc test was used to determine which age groups differ significantly on all five representations.

Subsequently, a follow up MANOVA (MANOVA 2) was performed to determine more accurately when deterioration starts. The participants were regrouped based on age as follows: 18 – 25, 41 – 45, 46 – 50, 51 – 55, 56 – 60, 61 – 65, 66 – 69 and >69. Participants between the ages of 26 and 40 were excluded from analysis, since the first MANOVA showed no significant difference in quality on each of the representations in comparison to the young adult group. The independent variable was age groups and the dependent variables were the standardized scores on each of the representations (AFoR, EFoR, LK, RK and SK). Since the brain peaks between the ages of 18 and 25 (Kolb & Whishaw, 2015), both structurally and functionally, the age group 18 – 25 was used as a reference group. That is to say, a significant difference between this group and any of the other groups was considered to be an indicator of deterioration. Before interpreting the analyses, three assumptions were checked. First, the Kolmogorov-Smirnov test of normality was used to check if there was multivariate normality. Second, the Box’s M Test of Equality of Covariance Matrices was used to check for homogeneity of variance-covariance matrices. Last, homogeneity of error variances was checked by running Levene’s Test of Equality of Error Variances. After interpreting the univariate tests, a Games-Howell post hoc test was used to determine which age groups differ significantly on all five representations.

Results

Raw scores

Table 2. *Raw scores on all five aspects of navigation behaviour. The scores are presented per age group (as grouped in MANOVA 1).*

Age group*	LK, mean (SD)**	EFoR, mean (SD)**	AFoR, mean (SD)**	RK, mean (SD)***	SK, mean (SD)***
18-25	7.2 (.9)	4.2 (1.4)	4.5 (1.6)	2.9 (.9)	2.4 (1.0)
26-40	7.2 (.9)	4.2 (1.4)	4.5 (1.6)	2.9 (.9)	2.4 (1.0)
41-55	6.9 (1.1)	3.9 (1.4)	4.1 (1.6)	2.7 (1.0)	2.2 (1.0)
56->69	6.8 (1.0)	3.6 (1.4)	4.0 (1.5)	2.5 (1.0)	2.2 (1.0)

Note: LK = landmark knowledge, EFoR = egocentric frame of reference, AFoR = allocentric frame of reference, RK = route knowledge and SK = survey knowledge

* 18 – 25 (young adults), 26 – 40 (adults), 41 – 55 (middle aged adults), and 56 – >69 (old adults)

** a maximum score of 8 could be achieved on this aspect.

*** a maximum score of 4 could be achieved on this aspect.

Table 3. *Raw scores on all five aspects of navigation behaviour. The scores are presented per age group (as grouped in MANOVA 2).*

Age group	LK, mean (SD)*	EFoR, mean (SD)*	AFoR, mean (SD)*	RK, mean (SD)**	SK, mean (SD)**
18-25	7.2 (.9)	4.2 (1.4)	4.4 (1.6)	2.9 (.9)	2.4 (1.0)
41-45	7.0 (1.0)	3.9 (1.3)	4.1 (1.5)	2.7 (1.0)	2.2 (1.1)
46-50	6.9 (1.0)	4.0 (1.4)	4.1 (1.7)	2.7 (1.0)	2.3 (1.1)
51-55	6.8 (1.2)	3.8 (1.4)	4.1 (1.6)	2.6 (1.0)	2.3 (1.0)
56-60	6.9 (1.1)	3.8 (1.3)	4.1 (1.5)	2.6 (1.0)	2.3 (1.0)
61-65	6.9 (1.0)	3.5 (1.3)	4.1 (1.3)	2.5 (.8)	2.3 (.9)
66-69	6.7 (1.0)	3.7 (1.4)	3.9 (1.5)	2.5 (1.0)	2.1 (1.0)
>69	6.7 (1.0)	3.5 (1.4)	3.7 (1.5)	2.3 (1.0)	2.1 (1.0)

Note: LK = landmark knowledge, EFoR = egocentric frame of reference, AFoR = allocentric frame of reference, RK = route knowledge and SK = survey knowledge

* A maximum score of 8 could be achieved on this aspect.

** A maximum score of 4 could be achieved on this aspect

As can be seen in both Table 3 and Table 4, the raw scores on each aspect decrease as age increases. The results of both MANOVA's will point out whether the decreases of these raw scores are significant.

Assumptions MANOVA 1

According to the outcomes of the Kolmogorov-Smirnov test of normality, the four age groups significantly deviated from normality on all five dependent variables ($p < .001$ for every group on all variables). Even though the data significantly deviated from normality, this was not a problem for running the MANOVA. Since *n* > 20 for every group, the test was robust to non-normality.

Box's M Test of Equality of Covariance Matrices was not statistically significant at $p < .001$, $F(45, 14519613) = 1.75$, $p = .001$. This means that there were no significant differences between the covariance matrices. Accordingly, Wilk's Lambda was a fitting test to use.

Levene's Test of Equality of Error Variances did not reach significance on the EFoR, $F(3, 2587) = .087$, $p > .05$. Therefore, the variance on this variable was equal across the groups. However, this did not apply to LK, $F(3, 2587) = 4.18$, $p < .01$, the AFoR, $F(3,587) = 5.01$, $p < .01$, RK, $F(3, 2587) = 12.50$, $p < .001$, and SK, $F(3, 2587) = 4.52$, $p < .01$. As a result, a Games-Howell test was used in post hoc analysis. This is a non-parametric post hoc test which is robust to heterogenous variances (Games & Howell, 1976).

Multivariate and univariate tests of MANOVA 1

Table 4. *univariate test results of MANOVA 1. The independent variable is age groups.*

Dependent Variables	df	F	Sig.	Partial eta-squared
Landmark knowledge	3	25.26	< .001	.028
Allocentric frame of reference	3	18.24	< .001	.021
Egocentric frame of reference	3	26.85	< .001	.030
Route knowledge	3	35.99	< .001	.040
Survey knowledge	3	5.99	< .001	.007

According to the outcome of Box's M test, Wilk's Lambda was an appropriate test to use in interpreting the multivariate test. Using an alpha level of .05, Wilk's Lambda proved to be significant, Wilk's $\Lambda = .93$, $F(15, 7130.93) = 13.16$, $p < .001$. Thus, there were significant differences among the age groups on one or more of the dependent variables. Furthermore, the partial eta-squared, $\eta^2_{partial} = .025$, showed that 2.5% of the multivariate variance of the dependent variables is associated with age. Accordingly, the effect size of partial eta-squared was small to medium.

Since the multivariate test reached significance, the univariate test results were examined. The test results are shown in Table 4. Using an alpha level of .05, a statistically significant main effect for age was observed on all five dependent variables. Moreover, the partial eta-squared of LK, the AFoR, the EFoR and RK were of small to medium size. The partial eta-squared of SK, however, is very small.

Assumptions MANOVA 2

The Kolmogorov-Smirnov test of normality showed that all eight groups significantly deviated from normality on all five dependent variables (p < .001 for every group on all variables). However, since n > 20 for every group, the test was robust to non-normality.

The Box's M Test of Equality of Covariance Matrices showed that there were no significant differences between the covariance matrices, F(105, 2598794) = 1.24, p = .051. Accordingly, Wilk's Lambda was a fitting test to use.

Last, Levene's Test of Equality of Error Variances showed that the variance on the EFoR was equal across all age groups, F(7, 1987) = 362, p = .924. However, this did not apply to LK, F(7, 1987) = 2.80, p < .01; the AFoR, F(7, 1987) = 2.67, p < .01; RK, F(7, 1987) = 4.30, p < .001 and SK, F(7, 1987) = 2.08, p < .05. Therefore, for this MANOVA, a Games-Howell test was also used in post hoc analysis.

Multivariate and univariate tests of MANOVA 2

Table 5. *univariate test results of MANOVA 2. The independent variable is age groups.*

Dependent Variables	**df**	**F**	**Sig.**	**Partial eta-squared**
Landmark knowledge	7	8.99	< .001	.031
Egocentric frame of reference	7	9.38	< .001	.032
Allocentric frame of reference	7	6.29	< .001	.022
Route knowledge	7	10.14	< .001	.034
Survey knowledge	7	2.9	< .01	.010

Since Box's M test was not significant, Wilk's Lambda was a fitting test to use in interpreting the multivariate test. Using an alpha level of .05, Wilks Lambda was found to be significant, Wilk's Λ = .93, F(35, 8344.16) = 4.4, p < .001. So, there were significant differences among the age groups on one or more of the dependent variables. Moreover, the partial eta-squared, $\eta^2_{partial}$ = .015, showed that 2.5% of the multivariate variance of the dependent variables is associated with age. The effect sice of the partial eta-squared was small.

The previous test results proved to be significant, so the univariate test results were examined. The univariate test results are shown in Table 5. Using an alpha level of .05, a statistically significant main effect for age was observed on all five dependent variables.

Moreover, the partial eta-squared of LK, the EFoR the AFoR and RK were of small to medium size. However, the partial eta-squared of SK is very small.

Post hoc analyses

Table 6. *An overview of the mean z-scores and significant differences per age group (as grouped in MANOVA 1).*

Age group*	LK, mean	EFoR, mean	AFoR, mean	RK, mean	SK, mean
18-25	$.21^{c, d}$	$.20^{c, d}$	$.16^{c, d}$	$.19^{c, d}$	$.11^{c}$
26-40	$.16^{c, d}$	$.16^{c, d}$	$.16^{c, d}$	$.23^{c, d}$	$.08^{d}$
41-55	$-.09^{a, b}$	$-.04^{a, b, d}$	$-.0.9^{a, b}$	$-.06^{a, b, d}$	$-.07^{a}$
56->69	$-.19^{a, b}$	$-.23^{a, b, c}$	$-.16^{a, b}$	$-.26^{a, b, c}$	$-.08^{a, b}$

Note: * = 18 – 25 (young adults), 26 – 40 (adults), 41 – 55 (middle aged adults), and 56 – >69 (old adults)
a = significantly deviates from 18-25 with $p < .025$
b = significantly deviates from 26-40 with $p < .05$
c = significantly deviates from 41-55 with $p < .025$
d = significantly deviates from 56->69 with $p < .05$

As the univariate tests of both MANOVA's were statistically significant on multiple dependent variables, the Games-Howell post hoc test was used to determine which age groups significantly differ from each other on these variables. An alpha level of .05 was used. Furthermore, in Table 6, an overview of the mean z-scores and significant differences per age group (as grouped in MANOVA 1) is given. This table will be elaborated upon multiple times in the following paragraphs.

Landmark knowledge

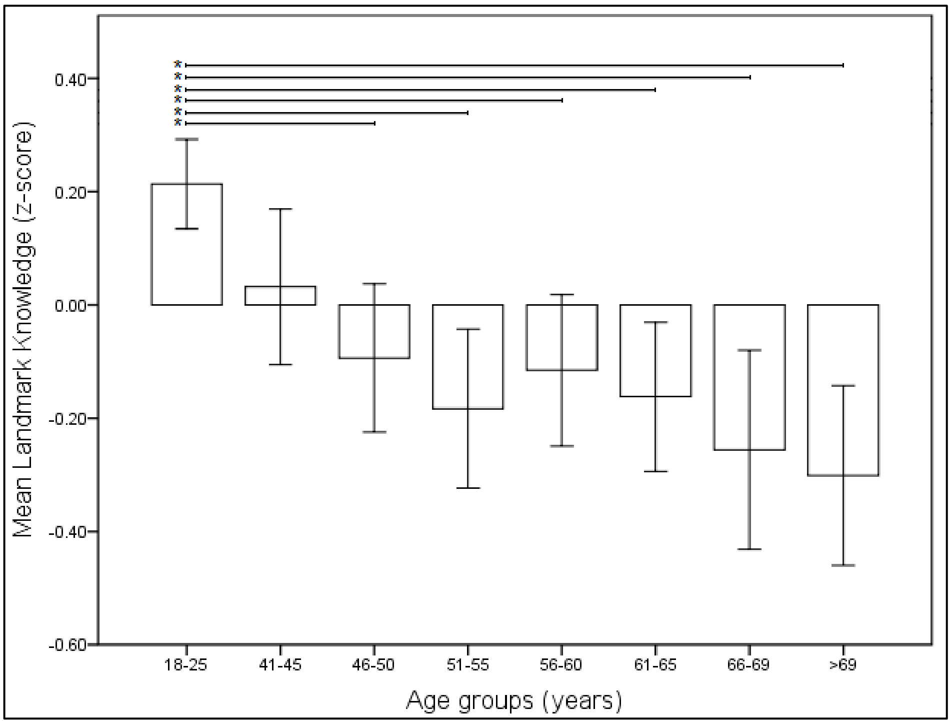

Figure 6. A visual overview of the mean z-scores and significant differences per age group on LK (as grouped in MANOVA 2). The error bars represent the Standard Error of the Mean.

Note: * = a significant difference was found with $p < .01$

As shown in Table 6, The young adults and adults did not significantly differ from each other on this variable, $p = .776$. Furthermore, middle aged adults were found to perform significantly worse than both young adults and adults. Old adults were also found to perform significantly worse than young adults and adults. However, no significant difference was found between middle aged adults and old adults, $p = .207$.

As can be derived from Figure 6, from the age group 46 – 50 on, all groups performed significantly worse than the reference group, thus indicating that the quality of one's usage of LK starts to deteriorate between the ages of 46 and 50.

Egocentric frame of reference

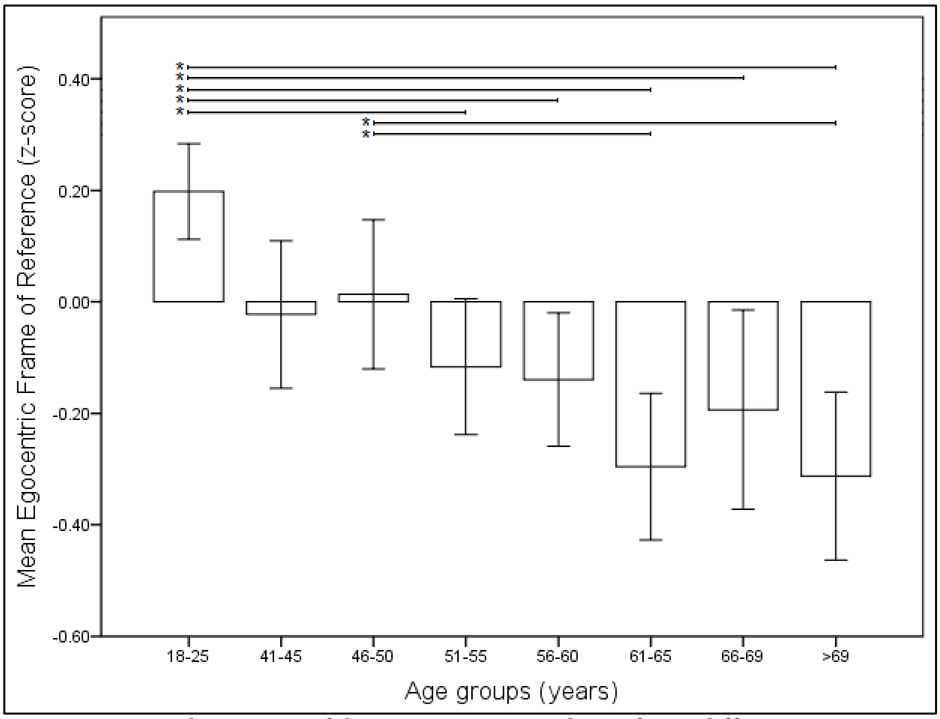

Figure 7. A visual overview of the mean z-scores and significant differences per age group on the EFoR (as grouped in MANOVA 2). The error bars represent the Standard Error of the Mean.

Note: * = a significant difference was found with $p < .05$

Young adults and adults did not significantly deviate from each other on this variable, $p = .949$. Moreover, as can be seen in Table 6, middle aged adults performed significantly worse than young adults and adults, but better than old adults. Thus, middle aged adults used the EFoR less efficiently than young adults and adults. In addition, old adults use it even less efficient than middle aged adults. Needless to say, the quality of the EFoR in old adults is significantly worse than young adults, adults and middle aged adults.

As shown in Figure 7, in the follow-up analysis, all age groups from 51 – 55 and up significantly differed from the reference group. Also, 46 – 50 performed significantly better than 61 – 65, $p < .025$, and >69, $p < .05$.

Allocentric frame of reference

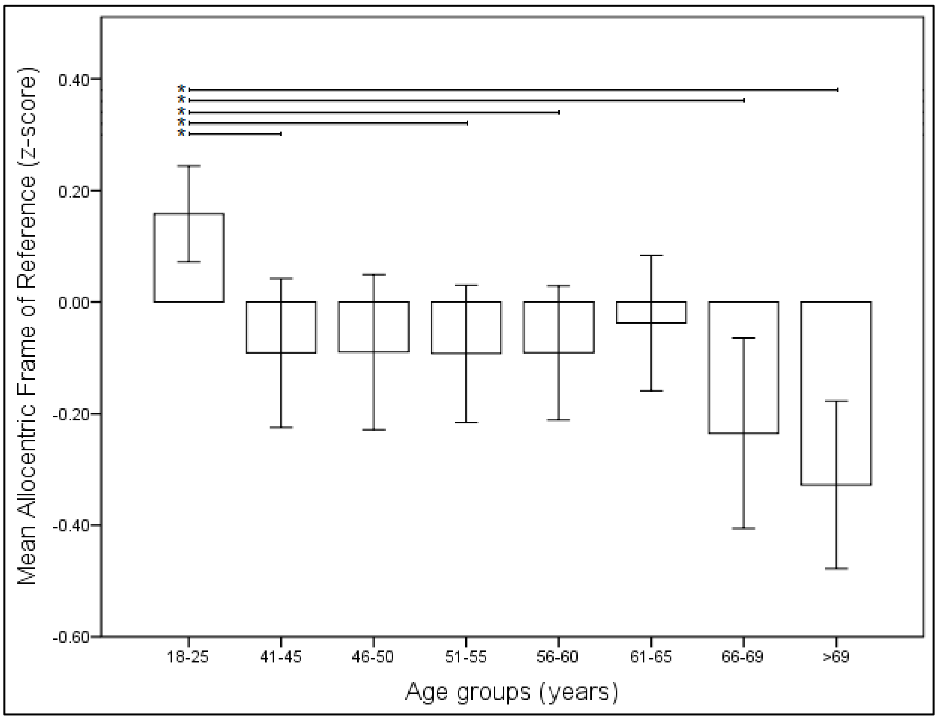

Figure 8. A visual overview of the mean z-scores and significant differences per age group on the AFoR (as grouped in MANOVA 2). The error bars represent the Standard Error of the Mean.

Note: * = a significant difference was found with $p < .05$

On this variable, there was no significant difference found between young adults and adults, $p = 1.000$. Furthermore, as shown in Table 6, middle aged adults used AFoR significantly less efficient than young adults and adults. However, there was no significant difference between middle aged adults and old adults, $p = .593$. Moreover, old adults do perform significantly worse than young adults and adults.

The follow-up analysis showed that a total of five groups significantly differed from the reference group: 41 – 45, 51 – 55, 56 – 60, 66 – 69 and >69, as can be seen in Figure 8. The groups 46 – 50, $p = .051$, and 61 – 65, $p = .146$, did not significantly differ from the reference group.

Route knowledge

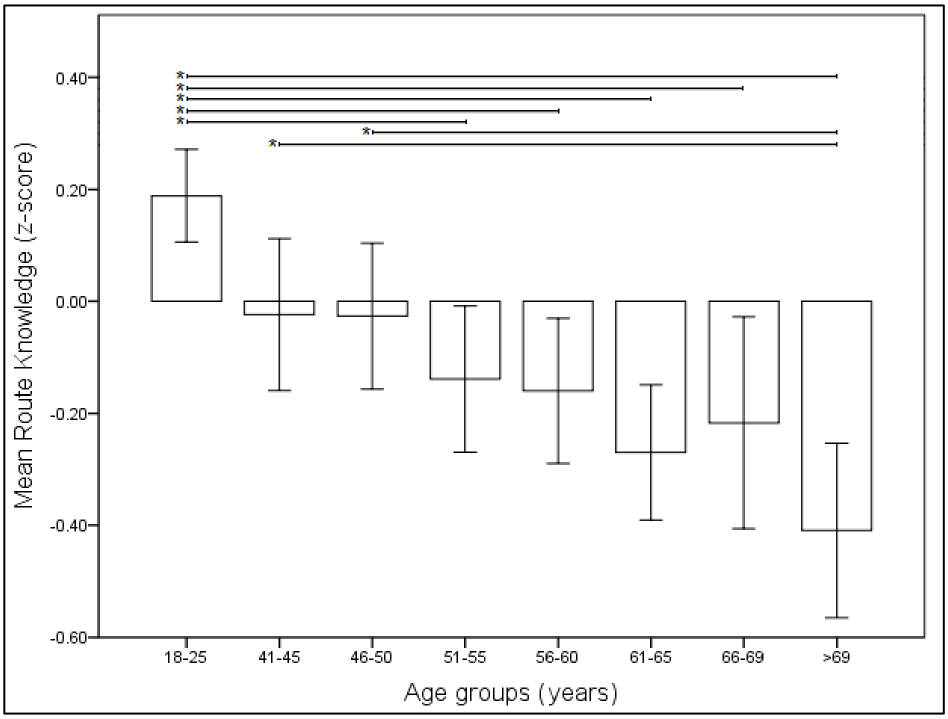

Figure 9. A visual overview of the mean z-scores and significant differences per age group on RK (as grouped in MANOVA 2). The error bars represent the Standard Error of the Mean.

Note: * = a significant difference was found with $p < .01$

Young adults and adults did not significantly deviate from each other on this variable, $p = .850$. Similar to the EFoR, middle aged adults performed significantly worse than young adults and adults, but better than old adults. Also, old adults performed significantly worse than young adults and adults. These results are shown in Table 6.

As can be seen in Figure 9, in the follow-up analysis, all age groups from 51 – 55 and up significantly differed from the reference group. Also, the groups 41 – 45 and 46 – 50 performed significantly better than >69.

Survey knowledge

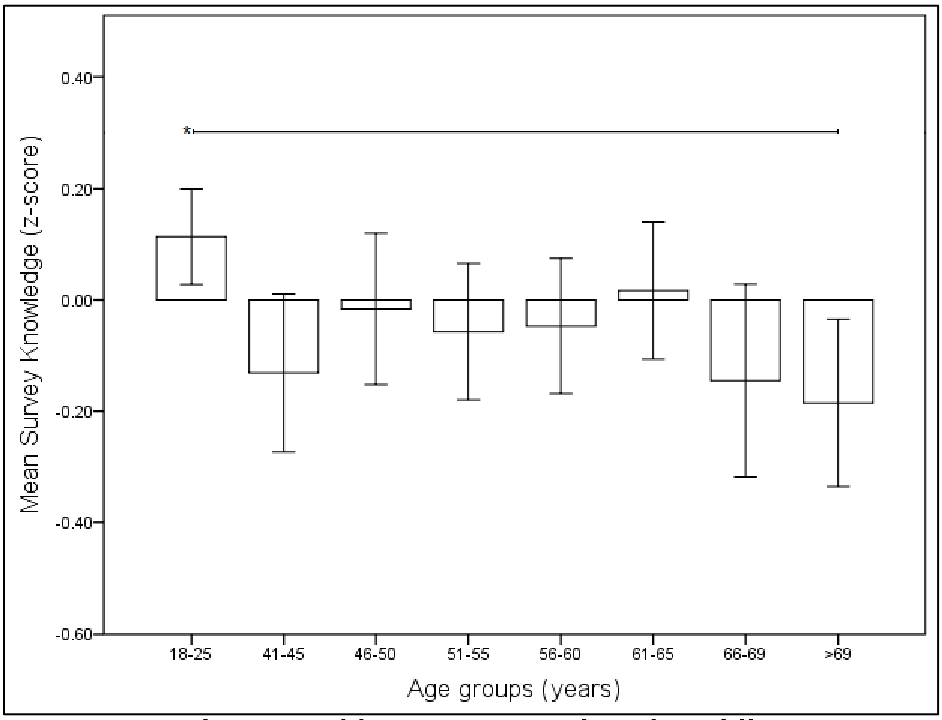

Figure 10. A visual overview of the mean z-scores and significant differences per age group on SK (as grouped in MANOVA 2). The error bars represent the Standard Error of the Mean.

Note: * = a significant difference was found with p < .025

On this variable, young adults and adults did not significantly deviate from each other, *p* = .919. Also, middle aged adults did not use SK significantly less efficient than adults, *p* = .066, and old adults, *p* = .994, but they did use it significantly less efficient than young adults, as can be seen in Table 6. Furthermore, old adults use SK significantly less efficient than both young adults and adults.

Interestingly, the follow up analysis showed only one significant result. The age group >69 is the only group that performed significantly worse than the reference group, as can be seen in Figure 10. So, the results found for middle aged adults in the previous analysis were not backed up by the follow up analysis.

Discussion

In current literature, it is already known that multiple aspects of navigation behaviour deteriorate as age increases. For example, Head and Isom (2010) showed that old adults recalled less landmarks they encountered in an environment than young adults. However, it was not yet known at which specific ages these deficiencies emerge. Also, never before was a functional model of navigation used to create a characterisation of the navigation behaviour in the elderly. By providing such a characterisation, a regular pattern of aging is established. Any deviation from this pattern can subsequently be used in the interpretation in a clinical context. As was expected, all aspects of navigation according to the model of Claessen and Van der Ham (2017) were affected by age. However, all aspects followed a different pattern of deterioration.

First, the results showed that adults between the age of 46 and 50 years and older significantly deviated from 18- to 25-year-olds on LK. This implies that LK substantially deteriorates between the age of 46 and 50 years. However, the lack of a significant effect between old adults and middle-aged adults indicated that no further considerable deterioration occurs. The deterioration in LK may be due to the reduction in hippocampal volume associated with the aging process (Grady et al., 1999), as spatial memory was found to be related to activation of the hippocampus (Prerau, Lipton, Eichenbaum & Eden, 2014). Since some types of memory are thought to decline from middle age (Nyberg & Bäckman, 2004), this might clarify why the deterioration in landmark knowledge occurred 10 years earlier than hypothesized.

The quality of the EFoR starts to deteriorate between the age of 51 and 55 years. Since the EFoR relies on a fronto-parietal network (Committeri et al., 2004), the deterioration may be the result of the less consistent recruitment of this network, as was found to be the case in older adults (Marstaller, Williams, Rich, Savage and Burianová, 2015). However, this does not explain why the deterioration occurred 10 years earlier than hypothesized. Perhaps the changes in the fronto-parietal network occur earlier than is currently known. Furthermore, a significant difference was also found between middle aged adults and old adults. More specifically, 46- to 50-year-olds significantly differed from 61- to 65-year-olds and adults older than 69 years. Hypothetically, this can be interpreted as a further substantial deterioration in the quality of the EFoR. However, since this age group did not cover the full middle aged adult group and 65- to 69-year-olds did not perform worse than 46- to 50-year-olds on this aspect of navigation behaviour, this remains to be up for debate. In addition, no clear drop was observed in the participants older than 69 years. However, this may be due to the fact that this effect could only have been observable in participants from 80 years of age and older (Ruggiero et al., 2016). This study was short of participants aged 70 and older.

The quality of one's usage of the AFoR seems to start deteriorating between the age of 41 and 45 years. However, participants within the age ranges of 46 to 50 and 61 to 65 years did not use the AFoR less efficiently than 18- to 25-year-olds. Figure 8 shows that within these age groups, participants seemed to perform on a higher, more stable level in comparison to the other age groups. The theory concerning reduced activation in both the posterior hippocampus and parahippocampal gyrus in older adults (Moffat et al., 2006), which may lead to the slower formation and less accurate usage of cognitive maps (Iaria et al., 2009), is still a plausible explanation regarding the deterioration of the AFoR. However, it does not explain why the deterioration occurred as early as the age of 41. Since the brain starts to structurally and functionally deteriorate from the age of 40 (Peters, 2006), it is possible that the reduction in activity of the posterior hippocampus and parahippocampal gyrus occur earlier than currently known.

With regard to RK, the pattern of aging was very similar to that of the EFoR. The significant effects between the reference group and all age groups from 51 to 55 years and older indicated that from the age of 51, RK was used significantly less than it was between the ages of 18 and 25 years. Furthermore, up until the age of 50 years, RK was used significantly more in comparison to adults older than 69 years. The similarity in course of deterioration to the EFoR may be due to the relationship between these two aspects of navigation behaviour, as RK is considered to be an egocentric representation of paths (Montello, 1998; Claessen & Van der Ham, 2017).

Finally, SK did not substantially deteriorate until the age of 69. As Figure 10 shows, the usage of SK remained around the same level as age increased. Even though SK is related to the AFoR (O'Keefe & Nadel, 1978), the course of deterioration was not similar to that of the AFoR.

Both RK and SK recruit a occipito-fronto-parieto-temporal network and associated structures (Latini-Corazini et al., 2010). The deterioration in both aspects may be due to a combination of earlier mentioned functional and structural changes, such as a reduction in hippocampal volume (Grady et al., 1999), a reduction in activation of the hippocampus and parahippocampal gyrus (Moffat et al., 2006) and perhaps even the less consistent recruitment of the fronto-parietal network (Marstaller et al., 2015). However, this does not clarify why RK and SK start to deteriorate 10 years earlier and 20 years later than hypothesized, respectively.

With regard to the discrepancies between the ages at which deterioration was hypothesized to occur and the actual outcome, the following might be a possible explanation for LK and the AFoR. The hypotheses were based on the age ranges of the old adult groups used in relevant literature. In most articles, participants are labelled as old adults when they are around the age of 50. In addition, the old adults are often only compared to a young adult group: middle aged adult groups lack in these studies (Head & Isom, 2010; Iaria et al., 2009). So, a possible significant effect for middle aged adults is easily overlooked. Also, the small amount of research done on SK and RK might have contributed to wrongly drafted hypotheses.

This study comes with a number of limitations. First, for the young adult, adult and middle aged adult groups, there was no even balance with regard to gender. As can be seen in Table 1, these groups contain around twice as many females than males. Since no analysis on gender differences has been performed, it is not clear whether this affected the outcomes. Furthermore, this study was short of participants older than 69 years of age. There were only 169 participants older than 69 years of age in total, half of which were aged 70 to 73 years. Every subsequent age was represented by only 1 to 10 participants. Had there been more participants in this age range, more detailed conclusions could have been made regarding adults with an age above 69. For example, Ruggiero et al. (2016) found that a clear drop in the quality of the EFoR occurred from the age of 80 years. Had this study included more participants aged 70 years and older, this finding could have been examined more carefully.

Future studies should focus more on adults from the age of 70 years and older. Relatively little is known about this specific group regarding navigation behaviour. Even though deterioration in navigation behaviour occurred 30 to 20 years before one reaches the age of 70 years, the rate of decline of the volume of the brain particularly increases in individuals aged 70 years and older (Scahill et al., 2003). This might affect navigation behaviour further. In addition, it may be interesting to investigate whether the relationship between the EFoR and RK might have contributed to the similarity in aging patterns. Especially since the AFoR and SK did not show a similar aging pattern at all.

By providing regular patterns of aging for multiple aspects of navigation behaviour using age groups with a span of just 5 years, it is now known around what ages these aspects start to deteriorate. Also, since impairment in navigation might be a prodromal symptom of Alzheimer's disease and other neurodegenerative diseases (Hort et al., 2007), these aging patterns can be used in (early) diagnostics by interpreting deviations from the patterns in a clinical context. In addition, the outcomes of this study may be useful in the development of rehabilitation programmes for impairments in navigation.

In conclusion, this study collected data on the quality of multiple aspects of navigation behaviour in a sample of healthy participants from young adulthood to elderly age (18-100). By analysing the data, a characterisation of navigation behaviour was provided, using the functional model created by Claessen and van der Ham (2017). All aspects of navigation behaviour were affected by age. LK was found to substantially deteriorate from between the ages of 46 and 50 years. Furthermore, the EFoR and RK followed a similar pattern of aging, as both aspects started to deteriorate between the ages of 51 and 55 years. In contrast, the AFoR and SK did not follow a similar pattern of aging. The AFoR started to deteriorate between the ages of 41 and 45 years, with peaks emerging between ages of 46 and 50 years and 61 and 65 years. SK, however, remained intact until the age of 69 years and started deteriorating thereafter. Since all aspects are dependent of structures that are prone to grey matter loss (Grady et al., 1999; Resnick et al., 2003) and loss of activity (Moffat et al., 2006), it seems only natural that deterioration of navigation behaviour occurs. However, the EFoR, the AFoR, RK and SK did not seem to fit the currently known structural and functional patterns of deterioration. Perhaps the underlying mechanisms of aging that affect navigation behaviour are not yet fully known and explored. Moreover, providing regular patterns of aging for each of these aspects of navigation behaviour may contribute to both early diagnostics and development of rehabilitation programmes for navigation impairment. Since data regarding the quality of navigation behaviour in adults aged 70 years and older is limited in this study and other available literature, future studies should focus more on this particular age group.

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