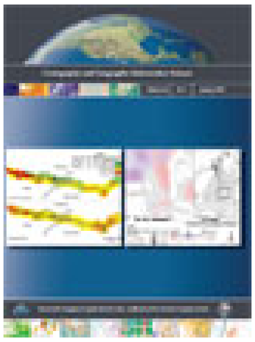

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# Perspective switch and spatial knowledge acquisition: effects of age, mental rotation ability and visuospatial memory capacity on route learning in virtual environments with different levels of realism

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**ABSTRACT**
We report on a study in which we examine if the visual design of virtual environments (VEs) affects visuospatial knowledge acquisition in younger and older adults with varying cognitive abilities in the context of navigational learning, *specifically* when a perspective switch is involved. Perspective switch between first-person and aerial-views is an important and commonly executed task in navigation; and it is a special case in studying the effects of aging on navigational performance as well, because, reportedly, it is particularly harder for older people. In a controlled experiment, our participants learned a route in first-person view VE, and reproduced what they learned in an aerial-perspective view in immediate and delayed recall stages. To examine the effects of (and interactions between) multiple factors involved in the experiment in relation to the given task, we provide an in-depth investigation of group differences in spatial knowledge acquisition when a perspective switch is required based on age, mental rotation abilities, and visuospatial memory capacity with three VE designs that differ in levels of realism. Our findings based on the recall accuracy of 81 (42 younger, 39 older) participants in sketching tasks demonstrate significant differences across VE types, overall, in favor of our custom-designed VE in this demanding task. Furthermore, we demonstrate that age and visuospatial memory abilities are strong moderating factors, explicitly in this sketching task that requires a perspective switch, irrespective of VE types.

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**KEYWORDS**
Age; spatial ability; memory capacity; spatial knowledge acquisition; mental rotation; perspective switch; delayed recall

## Introduction

When people follow a route, it is commonly assumed that the spatial structure of the environment is encoded in the human mind, and translated into spatial knowledge (Golledge, Dougherty, & Scott, 1995). This spatial knowledge acquisition can be affected by the visuospatial information that a person experiences (e.g. *what* is in the scene, and *what is where* in the scene), as well as the individual differences such as prior experience levels, memory capacity, and spatial abilities. While the effect of some of these factors are well-documented in other contexts, their combined effects and interactions with age and long-term information retention in the context of route learning with custom-designed VEs are not well understood. More specifically, we do not know how aging, tasks that require perspective switching in spatial knowledge acquisition, and abilities (such as mental rotation ability and visuospatial memory capacity) interact with differently designed virtual environments designed for route learning. Perspective switching in navigational tasks is known to be especially difficult for older adults (Herman & Coyne, 1980; Inagaki et al., 2002), but would this be different if a route learning environment is deliberately modified in terms of visual content?

To address the gap stated above, in this paper we examine: 1) whether we can improve spatial knowledge acquisition linked to *perspective switching tasks* in the context of route learning by optimizing a VE's visual design, 2) how age, mental rotation abilities, and visuospatial memory capacity interact with different VE designs in spatial knowledge acquisition in perspective switching tasks during (virtual) route learning. We hypothesize that with a deliberate visualization design (i.e. manipulating the visual scene content with the intention to assist spatial knowledge acquisition in general), we can improve the rate of acquired spatial knowledge. In previous analyses, we have shown that such deliberate designs *do* assist people of different age groups in *tasks that require visuospatial information recall* (Lokka & Çöltekin, 2017b; Lokka, Çöltekin, Wiener, Fabrikant, & Röcke, 2018). Differently to our previous work, in this paper we examine if the observed effects persist in *tasks that require perspective switching* across different age ranges and *also*

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ability groups, and we believe age and ability will act as moderating factors irrespective of visualization design. Below we provide a concise literature review that our hypotheses are built upon.

### Understanding and measuring spatial knowledge acquisition

In general, acquiring spatial knowledge from a first-person view navigational experience is a non-trivial task, as it requires constantly filtering the relevant information from a plethora of visuospatial input. Spatial knowledge acquisition becomes even more complex if the experienced first-person view must be translated to a top-down aerial view. If a person is asked to produce a 2D sketch of the route they just walked, they must perform a mental rotation from the first-person perspective (a "street view") to an aerial perspective (a top-down view), creating a structural layout of the navigated space in their mind (Thorndyke & Hayes-Roth, 1982). The complexity of mentally transforming the first-person 3D experiences (i.e. the route knowledge) to metric and survey knowledge has been demonstrated in previous studies (Golledge et al., 1995). The reverse, i.e. transformations from a 2D map view to the "real" 3D world has been shown to be non-trivial too (Kiefer, Giannopoulos, & Raubal, 2014). Importantly, it has also been shown that the complexity of the mental transformation during perspective switch in the context of route learning differs widely among individuals (Ishikawa & Montello, 2006). Besides the perspective shift in the visual experience and individual differences, the nature of the task is also important. For tasks requiring verbal descriptions of a learned layout, people who acquired spatial knowledge through direct exposure (from a first-person view) could provide descriptions *only* based on route knowledge, while people who learned from a map (from a top-down view) could provide descriptions *both* based on route and survey knowledge (Taylor & Tversky, 1996). These findings support the position that the experiences based on direct exposure to the environment provides limited assistance in acquiring survey knowledge. Shelton and McNamara (2004) provided further evidence that perspective switching (or shifting) introduces complications. In their experiment, keeping the "test view" (i.e. when the participant needs to recognize the layout) similar to the view during encoding was beneficial in recognition speed (Shelton & McNamara, 2004). Another group of researchers compared two study groups in tasks regarding survey knowledge acquisition, and also concluded that acquiring survey knowledge requires more cognitive effort than acquiring route knowledge (Van Asselen, Fritschy, & Postma, 2006). In summary, performing additional mental rotations (either because of changes in orientation or perspective) appears to have cognitive costs.

Spatial knowledge acquisition is often evaluated by measuring the success rates in various tasks, such as pointing tasks (i.e. judgement of relative direction), distance estimations, identification of the shortest route to a target, and producing sketch maps of the learned route among others (Wang, 2017). Use of sketch maps have received criticism due to (i) the variability of the tested environments, (ii) the subjectivity of the evaluation of accuracy, and (iii) the inability to control the participant's experience (Ishikawa & Montello, 2006). Nevertheless, sketch maps remain as a common metric in spatial knowledge acquisition studies (Appleyard, 1970; Billinghurst & Weghorst, 1995; Blades, 1990; Curtis, 2016; Lynch, 1960; Witmer, Sadowski, & Finkelstein, 2002), possibly because they are a common, and fairly intuitive, way to describe a route. Proposing an objective evaluation scheme for sketch maps is a non-trivial task, and there is a lack of a clearly defined methodology (Billinghurst & Weghorst, 1995). However, various "rules of thumb" can be obtained from the related work. Some important factors to consider in evaluating a sketch map are (Ladd, 1970; Moore, 1976): number of landmarks, number of streets (Anacta, Wang, & Schwering, 2014), object classes (Billinghurst & Weghorst, 1995), and relative object positioning (Billinghurst & Weghorst, 1995). Ideally these factors are presented on a sketch map to "sufficiently" represent the experienced route, and from there one can infer that the individual was successful in selecting relevant information, and in mentally processing the perspective switch.

The examples reviewed so far stress the difficulty of the acquisition of metric or survey knowledge from a top-down perspective, especially when the encoding occurs from a first-person perspective view. Aside from the factors related to the viewing perspective, a number of other factors affect spatial knowledge acquisition too. For example, it has been shown that if the learning is *intentional* or *incidental*, it affects spatial knowledge acquisition (Van Asselen et al., 2006). Importantly, it is well-understood that participant characteristics (i.e. individual and group differences, such as expertise, spatial abilities, and age) play a significant role in spatial knowledge acquisition.

### Effects of aging on spatial knowledge acquisition

In general, a wide range of abilities, skills, and attitudes play a role in successful spatial learning (Weisberg & Newcombe, 2016; Wolbers & Hegarty, 2010); and some of these skills can be assessed using standardized tests

(Ekstrom, French, Harman, & Dermen, 1976; Vandenberg & Kuse, 1978). In spatial knowledge acquisition, differences in individuals' spatial abilities and memory capacity are considered especially relevant (Çöltekin, Francelet, Richter, Thoresen, & Fabrikant, 2018; Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006; Hurlebaus, Basten, Mallot, & Wiener, 2008; Ishikawa & Montello, 2006; Montello, 1998; Muffato, Meneghetti, & De Beni, 2016; Muffato, Meneghetti, Di Ruocco, & De Beni, 2017; Wolbers & Hegarty, 2010). Importantly, these abilities are affected by age-related cognitive decline. Specifically, it is well-known that aging negatively correlates with navigational learning (Moffat, 2001; Wiener, Kmecova, & de Condappa, 2012; Wolbers, Dudchenko, & Wood, 2014) and performance in spatial memory (Richmond, Sargent, Flores, & Zacks, 2018). This appears to be true especially in allocentric tasks (Fricke & Bock, 2018). Thus, aging is necessary to consider as a factor in spatial knowledge acquisition studies.

It appears that switching from an egocentric (e.g. first-person view) perspective to an allocentric (e.g. top-down view) one is a "weak spot" particularly for older people. Several studies featuring tasks that require a perspective switch demonstrated that older people commit more mental rotation errors than younger people (e.g. Herman & Coyne, 1980; Inagaki et al., 2002). Furthermore, when there are many orientation changes throughout the learned route, older adults are less effective in environmental learning, irrespective of the perspective in which the environment is experienced (Yamamoto, Fox, Boys, & Ord, 2018). In Yamamoto et al.'s (2018) study, learning a route from an egocentric representation impaired survey knowledge acquisition in older people, whereas learning from an allocentric representation did not, that is, results were comparable to that of younger people (Yamamoto & DeGirolamo, 2012). A recent study examining sketch map accuracy added further nuance to this finding: After learning from an allocentric representation, older adults' sketches were less accurate than those of younger adults, if *missed locations of landmarks* were used as a measure of accuracy (Muffato et al., 2017). However, authors demonstrated that when only *number of landmarks* is used as a measure of accuracy, age differences disappeared. In Muffato et al.'s (2017) study, visuospatial working memory capacity correlated with success irrespective of age (Muffato et al., 2017).

The examples reviewed above are only a small portion of the vast literature that demonstrates how individual and group differences can affect spatial knowledge acquisition, especially when there are orientation or perspective shifts during learning. The fact that spatial (and especially survey) knowledge acquisition is more difficult for some people than others highlights the necessity to address individual and group differences while designing visualizations (including VEs), so that visual displays, such as VEs, facilitate better spatial learning for all. The concept of *designing for all* in the geovisualization literature is well investigated, especially for maps (Reichenbacher, 2001). Maps that are "designed for all" respond to any accessibility issues, and accordingly adapt to user needs. Such maps (and visualizations) can be personalized, and/or optimized for group differences based on age and expertise (Nivala & Sarjakoski, 2005). By ensuring that designs are *accessible* to all, is reasonable to assume that they are *improved* for everyone, irrespective of abilities.

## *Virtual environments for route learning in navigational tasks*

VEs have long been used for studying navigation and spatial cognition. As opposed to the real world, VEs provide safe and controlled environments, thus, we can examine navigational behavior (and associated spatial learning) in response to a specific variable of interest, without other variables confounding. However, it is important to remember that the way these VEs are visually designed—for example, the amount, the quality, and the location of provided information within a VE (Lokka & Çöltekin, 2017a)—can have a strong impact on the spatial learning performance. Through a well-informed visualization design, one might be able to improve knowledge acquisition from VEs for everyone. Such an improvement might be especially relevant for those with lower abilities (e.g. people with lower visuospatial abilities, memory capacity, or older adults). It has been previously demonstrated that differently designed VEs facilitate spatial learning differently. More specifically, custom-designed VEs can improve short- and long-term recall performance in visuospatial tasks (Lokka & Çöltekin, 2017b). This effect is also relevant for older adults. With such custom designed VEs, older people improve their accuracy in visuospatial knowledge acquisition, and calibrate their confidence in tasks that *retain the viewing perspective* (Lokka et al., 2018). A well-considered adjustment of the visualization design is known to reduce cognitive load (Sweller, 1988), and we believe such an adjustment will also have direct effects on tasks that require *perspective switching*. A well-considered adjustment, for example, could include levels of realism in the context of working with VEs. High levels of visual realism have been shown to negatively correlate with cognitive load, and it can impair the rates of spatial knowledge acquisition, especially for people with lower spatial abilities (Lokka & Çöltekin, 2017b; Lokka et al., 2018). Despite the cognitive load it seems to introduce, people overwhelmingly *prefer* visually realistic displays to more abstract ones, possibly because of their resemblance to the real world and the associated feeling of familiarity (Çöltekin et al., 2017; Lokka et al., 2018; Smallman & John, 2005).

Because photo-realistic representations are popular, yet they might impair performance in tasks that are demanding on working memory; we believe a visualization solution that balances between preference and performance is using realistic photo-textures *selectively* in spatial learning tasks. Doing so highlights the important information that aids encoding relevant visuospatial features in the scene, yet keeps "enough" realism to simulate the *sense of place*, and to provide a reference (or an anchor) to the real world. When selectively showing the photo-textured features, an important design consideration is *where* these photo-textured features should be located. Besides their location, saliency of landmarks can be defined by semantic, visual, and structural elements, and each of these are important for the *attractiveness of landmarks* (Raubal & Winter, 2002). In this paper we focus on the *locations* of the highlighted features, because as soon as we highlight selected features, they serve as landmarks, and landmarks are important facilitators of spatial learning (Richter & Winter, 2014; Röser, Hamburger, Krumnack, & Knauff, 2012; Winter, Raubal, & Nothegger, 2005). Thus, in addition to adjusting levels of realism against cognitive load; we believe the photo-textured features (i.e. "landmarks") should be positioned in locations where people would (and would need to) pay attention, based on previous findings (Röser et al., 2012).

## *Hypotheses*

We implemented a visualization design solution that we believe would balance levels of realism for optimum route learning performance while remaining attractive to the users and called this solution "MixedVE". Previously, we tested the MixedVE against the two baseline VEs with younger participants in a variety of tasks that involve visual, spatial, and visuospatial recall of information and confirmed its value to our younger age group (Lokka & Çöltekin, 2017b). Furthermore, we already investigated how the MixedVE facilitates the recall of visuospatial information for older adults for visuospatial tasks, i.e. we examined the recall rates of both age groups in a task that did *not* involve perspective switching (Lokka et al., 2018). To acquire a holistic understanding of the effect of the MixedVE for navigational tasks, we now further investigate the MixedVE's performance in a *perspective switching task*; we compare participants' spatial knowledge acquisition in a route learning task where participants need to sketch a 2D top-down representation of a route they learned in a first-person perspective VE. We conducted the tests with the MixedVE against two other VEs: An abstract one with no visual cues (AbstractVE), and a fully photo-textured one that resembles a realistic environment (RealisticVE). We examine if the benefits offered by the MixedVE, specifically *for this task type*, transcends individual differences based on age, mental rotation ability, and visuospatial memory capacity. We believe that the MixedVE will provide benefits over the two alternatives we tested.

Comparing the MixedVE to the Abstract and Realistic VEs as described above (and illustrated in Figure 1), we specifically investigate: 1) whether the MixedVE assists in spatial knowledge acquisition in tasks that involve perspective switching more than the Abstract and Realistic VEs (measured in active sketching tasks); 2) whether the observed differences in the accuracy of acquired spatial knowledge in tasks that involve perspective switching (if any) are explained by differences in age, mental rotation (MRT) abilities, or visuospatial memory (VSM) capacity and how these interact with visualization types (the three VEs); and, 3) whether MRT and VSM tests predict the successful acquisition of the spatial knowledge in tasks that involve switching perspectives, especially in relation to different visualization types. Based on the literature, for each question framed above, we hypothesize the following:

(1) The MixedVE will facilitate better spatial knowledge acquisition in tasks that involve perspective switching (i.e. accuracy in sketching) than the other two VEs.
(2) Younger participants will produce more accurate sketches than older participants, irrespective of VE type; and, participants with higher MRT/VSM scores will outperform the participants with lower MRT/VSM scores irrespective of age or VE type.
(3) Irrespective of age, participants with higher VSM will outperform the participants with lower VSM in producing accurate sketches, particularly with the MixedVE and RealisticVE, as these provide potentially helpful photographic visual cues; whereas MRT will be most relevant to Abstract VE because this visualization type contains no (photographic) visual cues.

## Methods

To test our hypotheses, we conducted a controlled laboratory experiment. In our mixed-factorial design,

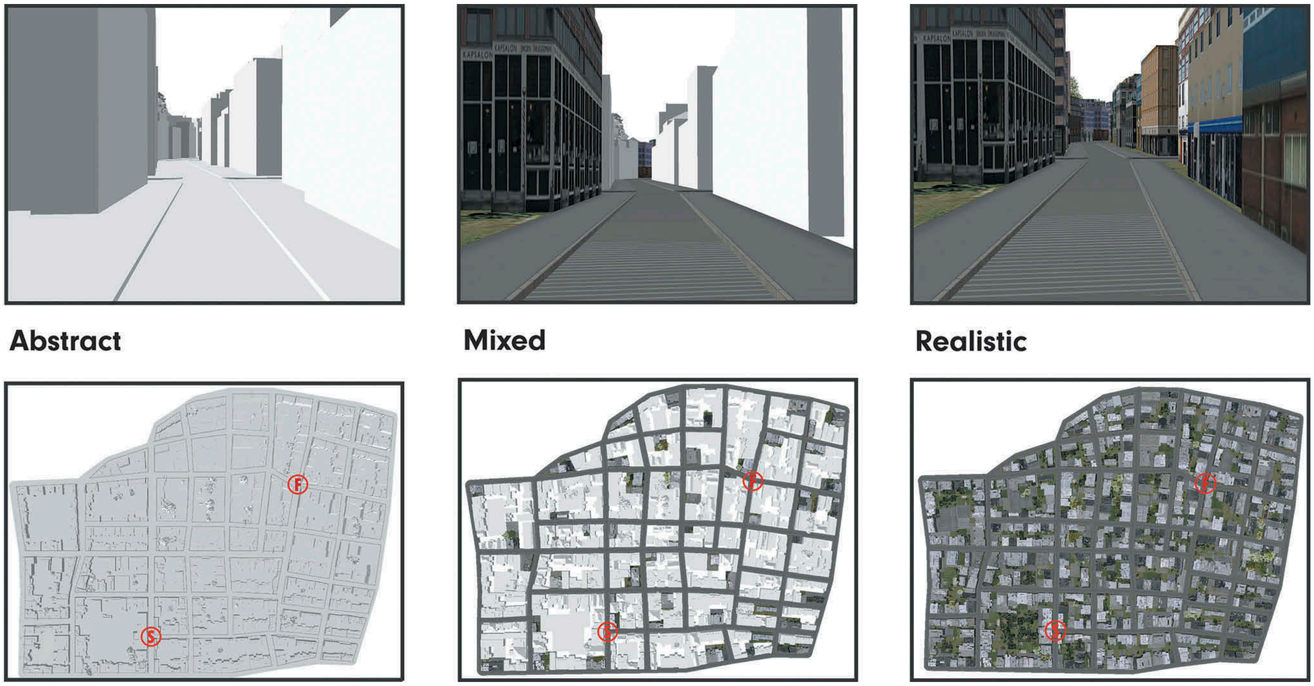


**Figure 1.** Top: The three experimental conditions in which all participants experienced a video drive-through: the abstract, mixed, and realistic VEs (left to right). Down: The 2D map views of each VE, on which participants sketched the respective routes they experienced in each VE from the memory. Start and end points were marked on the screenshots.

independent variables were: *age* as a between-subject factor (younger and older) and *visualization type* (Abstract, Mixed, Realistic VEs) as a within-subject factor. Participants were explicitly asked to learn a given route presented to them as a video. We have previously published two papers that are based on different data that are collected from the same participants, based on different experimental tasks, answering different research questions (Lokka & Çöltekin, 2017b; Lokka et al., 2018). In the experiment, participants performed a set of visuospatial recall tasks analyzed in Lokka and Çöltekin (2017b), along with an active *sketching task*. In this paper, we *only* focus on the latter task, which has not been analyzed before. During this active sketching task, the participants drew the route they experienced in the VEs on printed top-down screen shots of each VE (thus the visual cues in the baseline map differed according to the VE type, see Figure 1). We selected such a task for experimental control: The visual stimuli the participants experienced during the *encoding* were kept identical (i.e. everyone experienced the same visual scenes, thus did not have different landmarks), and the same was true for the visual stimuli at the *decoding* stage (i.e. 2D map views provided for the active sketching were identical). By keeping the visual variability in check, we ensure the comparability of the success rates we measure per task. Participants drew the sketches twice from the memory; thus, we measured *immediate recall* success right after they experienced the VEs, and *delayed recall* success a week later. The sketches were evaluated for their accuracy and completeness based on a scoring scheme, and this was our main dependent variable.

### Participants

A total of 81 volunteers took part in the experiment; 42 of them were younger (23 female, 20–30 yrs.) and 39 older (17 female, 65–75 yrs.). Younger participants were recruited by word of mouth, while the older participants were recruited via the participant pool of the University Research Priority Program "Dynamics of Healthy Aging" of the University of Zurich. We screened all participants for mild cognitive impairments as an inclusion/exclusion criteria; that is, they were included in the experiment if they achieved a score of 27 and above on the Mini Mental State Examination (MMSE) (O'Bryant et al., 2008).

### Materials

#### Stimuli

We conducted the experiment in a 3D visualization lab (Department of Geography, University of Zurich). VEs were shown on a large rear-projection display (2438mm x 1829mm), at 2.2m distance from the participants. The VEs featured a fictitious 3D city with buildings similar in style, shape and color to control for their possible effects on the memory because of their distinctiveness. We designed the angles at the intersection and turn points to control for visibility of features. We then selected two routes of equal length, with comparable visual information, and equal amount of "turns" (3 left, 3 right, 1 intersection continuing straight). VEs were shown as passive videos, deliberately avoiding any interaction from the participants, to make sure that participants were all exposed to the same information, for equal durations at equal speed. Routes were shown in a "driving simulation" at a constant eye level, with a fixed speed (30 km/h). We presented our fictitious city in three different visualization designs (Figure 1): the AbstractVE with no colors and no photo-textures, the RealisticVE with full visual realism with color photo-textures, and the MixedVE with a "combination" of the two in terms of realism. In the MixedVE, only the buildings at the intersection points (at critical locations) and toward the direction of turn were highlighted using color photo-textures. We also counterbalanced the content of the photo-textures for distinctness and memorability (Lokka & Çöltekin, 2017a). Furthermore, we highlighted the structural network (i.e. the road with the pavement) in the MixedVE, as this might be helpful in forming spatial knowledge.

### Assessment of individual differences

We used two standardized tests to assess participants' spatial abilities and visuospatial memory capacity: 1) *Mental Rotation Test (MRT)*. This test requires correctly discriminating rotated 3D objects from foils based on a reference shape (Vandenberg & Kuse, 1978). The MRT has been used as a measure for identifying differences in spatial abilities (Meneghetti, Borella, Pastore, & De Beni, 2014; Meneghetti, Muffato, Varotto, & De Beni, 2017; Muffato, Della Giustina, Meneghetti, & De Beni, 2015; Muffato et al., 2017), even though there are arguments for the dissociation between object-based and egocentric spatial transformations (Hegarty & Waller, 2004, p. 2) *Visuospatial Memory Test (VSM)*. This test measures visuospatial memory capacity based on a 2D city plan. Participants study a city plan that contains 12 visually different buildings, and later need to place these buildings in their correct location on a layout that does not contain buildings (Ekstrom et al., 1976).

### Experimental task

Participants were told that someone was driving them to their destination, but they would have to re-take this route again on their own later, thus should memorize the route to the best of their ability. Thus, the learning was intentional in the learning phase. At the response phase, similar to Krüger, Aslan, and Zimmer (2004) study, participants were provided with a printed 2D map of the area (top-down screenshots from each VE, on an A4 sheet, which were clear and legible), on which the position of the start and end points were marked (Figure 1). Participants were given the map with the north orientation (the initial orientation direction), and marked the route from memory (which they experienced in each VE during the experiment) on the given maps using a pen. This task, thus, measured spatial knowledge that requires a mental transformation from the first-person perspective to an aerial (top-down) perspective for the 2D sketch. Participants' initial orientation (heading direction) in the sketching task was the same as in the VEs (Shelton & McNamara, 2001).

### Procedure

Upon arrival at the visualization lab, participants read and signed a written consent form. We then introduced the setup and the experimental process, and immediately after, we began with the main experiment.

We displayed the scenario on the screen and instructed the participants to memorize the route(s) just before they experienced the virtual routes. Then they (passively) watched the videos of the two routes in all three environments (total six videos). Each video was shown only once. We controlled for the order of presentation of the environments with a Latin Square design. After experiencing all six videos, participants were asked to solve visuospatial tasks (Lokka & Çöltekin, 2017b; Lokka et al., 2018) and then sketch the followed route of the six walkthroughs in the order they experienced them. After a week, they returned to the lab and performed the standardized tests, along with the same sketching task of all six walkthroughs from the memory, without watching the videos again.

## Results

Participants' spatial knowledge acquisition was evaluated based on the accuracy and completeness of the sketches they drew (Figure 2 illustrates some examples). Specifically, sketches were evaluated for accuracy and completeness based on the following criteria: 1) number of turns (total, right and left), 2) correct direction of heading at the starting point, 3) correct direction of arriving at the end point, 4) correct direction of turn at each intersection point, 5) sequential order of turns (route patterns).

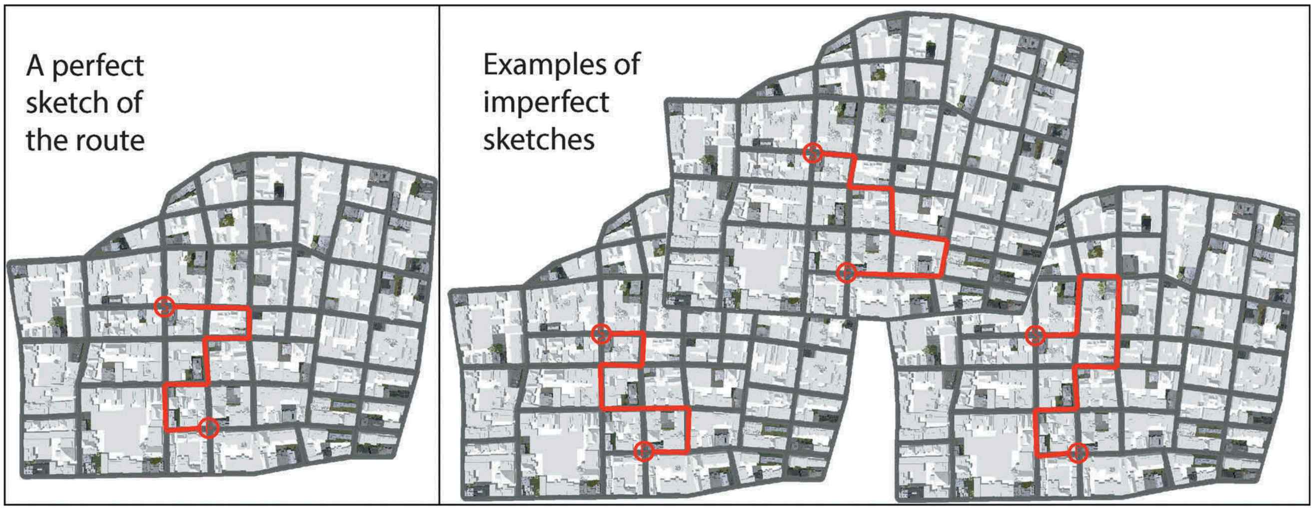


**Figure 2.** Example results from the sketching task. Left: A fully correct solution for one of the routes achieving a 100% score. Right: Three examples of participants' sketches of the same route with errors in terms of: number of turns, direction of turns, and sequential order of turns.

**Table 1.** Correlation matrix for the examined factors based on participant performance in the sketching task in both stages in all visualization conditions.

| | MRT | VSM | Age |
|---|---|---|---|
| Individual and group differences | | | |
| VSM | .38*** | - | |
| Age | −.45*** | −.62*** | - |
| Visualization conditions at the immediate (i) recall stage | | | |
| Abstract VE (i) | .26* | .33** | −.40*** |
| Mixed VE (i) | .27* | .30** | −.45*** |
| Realistic VE (i) | .20 | .24* | −.29** |
| Visualization conditions at the delayed (d) recall stage | | | |
| Abstract VE (d) | .25* | .32** | −.39*** |
| Mixed VE (d) | .22 | .39*** | −.44*** |
| Realistic VE (d) | .24* | .34** | −.39*** |

*** $p < .001$, ** $p < .01$, * $p < .05$.

Below we begin by presenting correlations between our main variables (MRT, VSM, age, visualizations, recall stage) to provide the overall findings; and then extend the analysis to each ability test (MRT and VSM) to identify main effects and interactions in depth.

After obtaining the scores for each participant's sketches in immediate and delayed recall stages; to get an overview of how all factors in the experiment interacted, we analyzed correlations between MRT, VSM, and age groups; both with each other and with the sketching success based on all VEs (Table 1).

## *The effect of spatial abilities on the sketching success*

To get a deeper understanding of the relationship between MRT and VSM scores and task success, we conducted two separate analyses of variance. Similar to Meneghetti, Gyselinck, Pazzaglia, and De Beni (2009) and Pazzaglia and De Beni (2006) who split their sample into high and low abilities, we grouped the participants based on a median split (Iacobucci, Posavac, Kardes, Schneider, & Popovich, 2015) (excluding the median values) into two groups for each test. The *High MRT* ($n$ = 36) vs. *Low MRT* ($n$ = 36), *High VSM* ($n$ = 39) vs. *Low VSM* ($n$ = 38) groups were treated separately in a mixed-design ANOVA, where we kept *age, recall stage,* and *visualization type* also as independent variables in both analyses.

### *MRT*

Figure 3 shows the overall differences based on age, recall stage, MRT abilities, visualization type, and the significant interactions based on the differences in participants' MRT scores.

We see that, irrespective of their MRT scores, younger participants outperform the older (Figure 3(a)); participants are overall more successful at the sketching task in the immediate recall stage than in the delayed (Figure 3(b)); and they are more successful in sketching task based on what they recalled from the MixedVE than the other two VEs (Figure 3(d)). We also see a clear pattern that the High MRT group outperforms the Low MRT group, irrespective of other factors (Figure 3(c)). A 2 (age) x 2 (recall stage) x 2 (MRT score) x 3 (visualization type) mixed-design ANOVA revealed that all observed differences in the sketching performance for all four independent

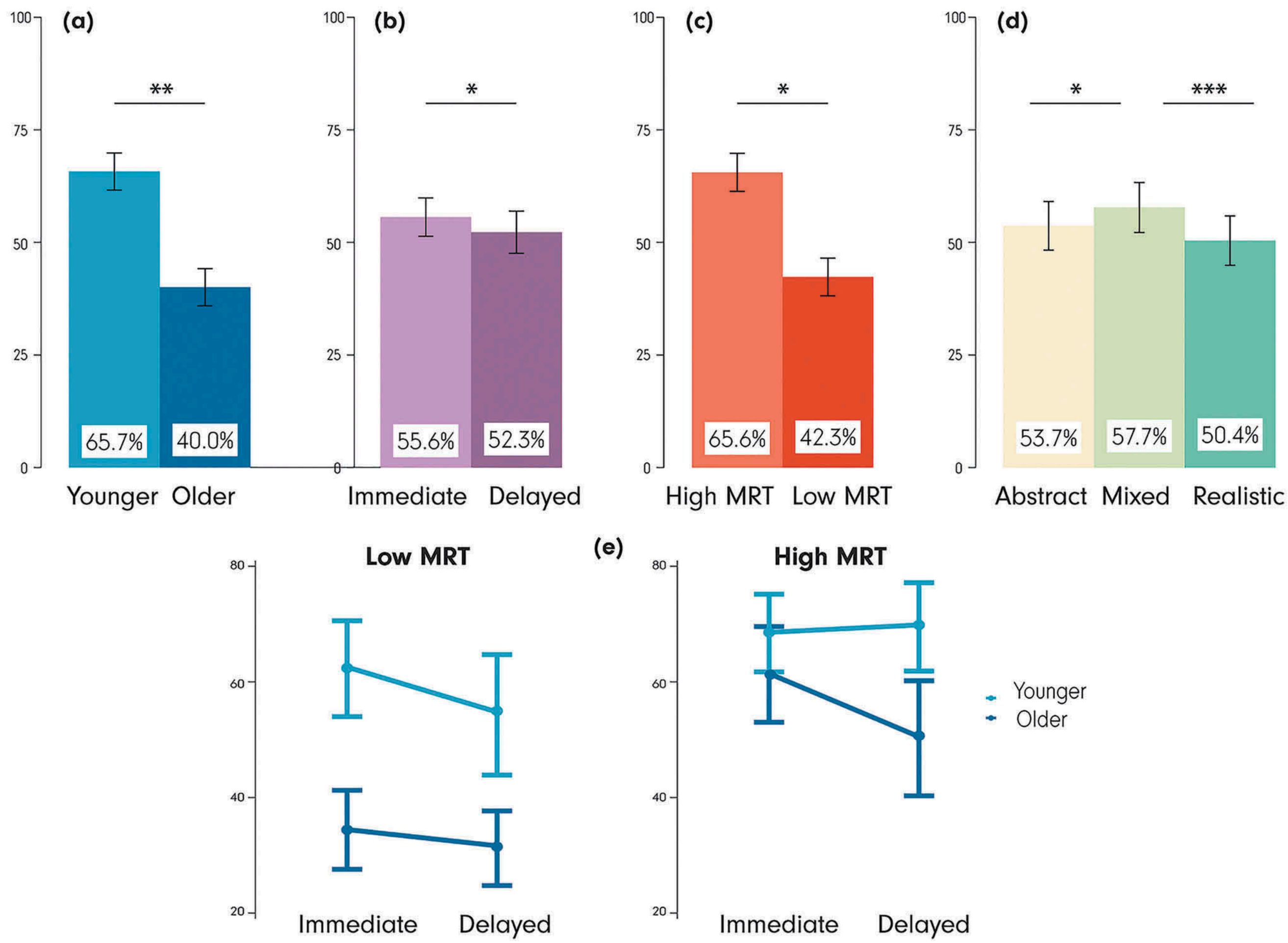


**Figure 3.** Main effects of (a) *age*, (b) *recall stage*, (c) *MRT score*, and (d) *visualization type* on sketching task and (e) significant interactions of *MRT ability x age x recall stage*.
*** $p < .001$, ** $p < .01$, * $p < .05$. Error bars: SEM.

variables are statistically significant; Figure 3(a)) *age* F(1, 68) = 7.81, $p < .01$, $\eta_p^2 = .08$, Figure 3(b)) *recall stage* F(1, 68) = 5.97, $p < .05$, $\eta_p^2 = .01$, Figure 3(c)) *MRT score* F(1, 68) = 5.79, $p < .05$, $\eta_p^2 = .06$, Figure 3(d)) *visualization type* F(2, 136) = 12.16, $p < .001$, $\eta_p^2 = .01$. Because there are three visualization conditions, we conducted pairwise comparisons, which revealed significant differences in participants' sketching performance (thus, "recall accuracy", as the sketches were drawn from the memory) between the three VEs: participants' overall average sketching performance was higher with the MixedVE than with the Abstract ($p < .05$, d = 0.12) and the Realistic VEs ($p < .001$, d = 0.22). Importantly, among the interactions between the four independent variables, only *age x MRT x recall stage* F(1, 68) = 4.31, $p < .05$, $\eta_p^2 = .01$ was significant (Figure 3(e)).

Because of this interaction effect, we examined the *forgetting rates* (differences in sketching performance between immediate and delayed recall stages) for older and younger participants. The analyses revealed no significant differences for the low MRT participants between the two age groups (i.e. they forget, or retain, a similar amount of information), whereas for the high MRT groups, the forgetting rate of the older participants is significantly higher than that of the younger participants (t(46.71) = −2.61, $p < .05$, r = .36).

### *VSM*

Figure 4 shows the results of the analyses based on the VSM sample. Note that the sample size for the VSM analyses is slightly different from sample size in the MRT analyses, because we removed the median scores from the pool, and the number of people who achieved the median score was different for the two tests (participants achieving median in: MRT: $n = 9$, VSM: $n = 4$). Despite this slight difference, we see that the results overall display a similar pattern (Figure 4).

First, descriptive statistics suggest that the younger participants outperform the older (Figure 4(a)); sketching task seems to be overall easier in the immediate recall stage than

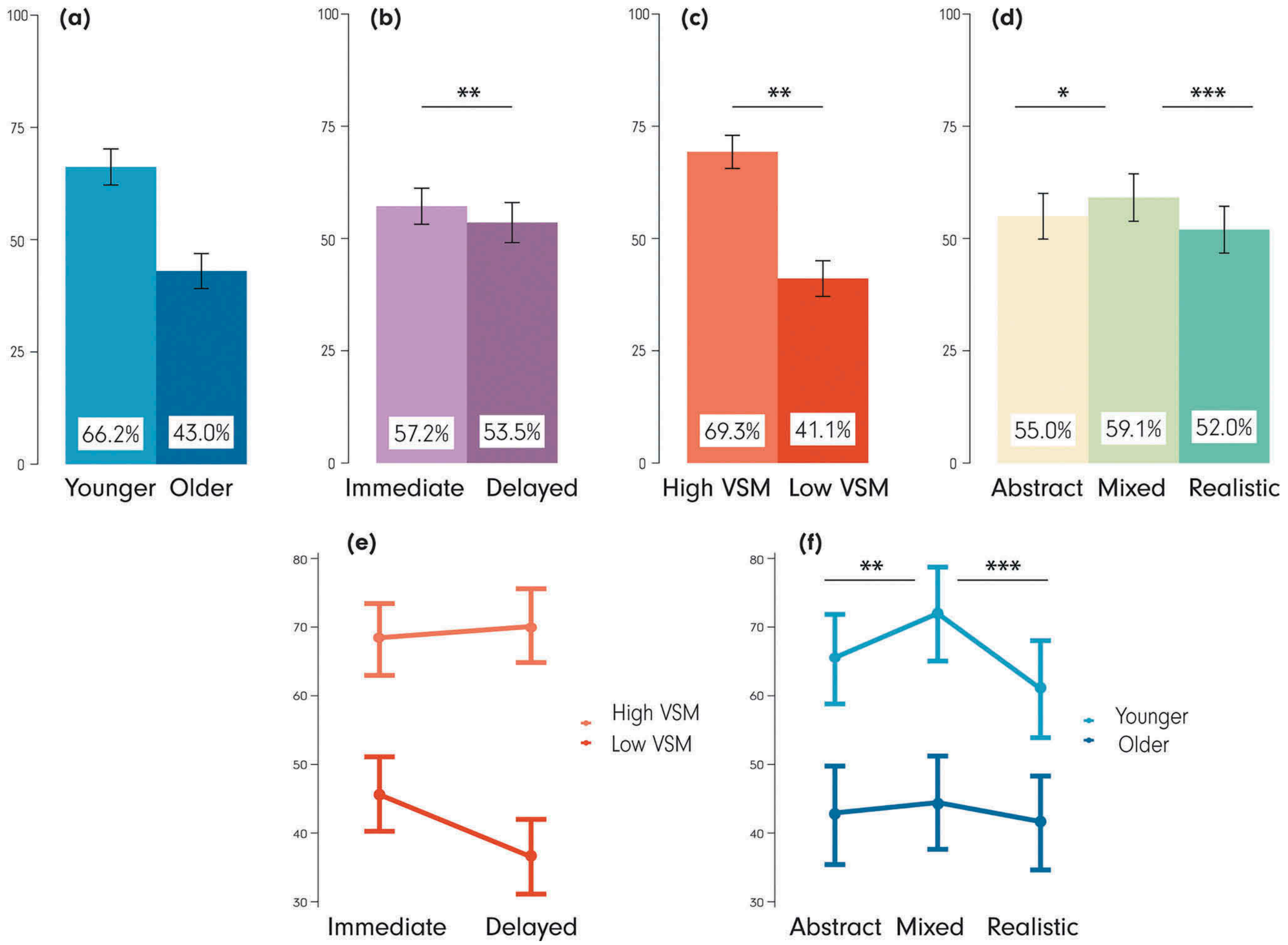


**Figure 4.** Main effects of (a) *age*, (b) *recall stage*, (c) *VSM scores*, and (d) *visualization type* on sketching task and significant interactions of (e) *VSM ability x recall stage* and (f) *age x visualization.*

*** $p < .001$, ** $p < .01$, * $p < .05$. Error bars: SEM.

in the delayed recall stage irrespective of other factors (Figure 4(b)), and again, MixedVE facilitates a higher success in sketching than the other two VEs (Figure 4(d)). High VSM group too, outperforms the low VSM irrespective of other factors (Figure 4(c)).

A 2 (age) x 2 (recall stage) x 2 (VSM score) x 3 (visualization type) mixed-design ANOVA revealed significant differences in the sketching performance for three out of four independent variables. Differences in sketching success based on *age* was not significant (F(1, 73) = 3.10, $p > .05$, $\eta_p^2 = .03$) (Figure 4(a)); whereas *recall stage* F(1, 73) = 8.17, $p < .01$, $\eta_p^2 = .01$ (Figure 4(b)); *VSM score* F(1, 73) = 10.79, $p < .01$, $\eta_p^2 = .11$ (Figure 4(c)); and *visualization type* F(2, 146) = 9.05, $p < .001$, $\eta_p^2 = .01$ (Figure 4(d)) led to statistically significant differences. For the visualization type, we again conducted pairwise comparisons, and observed significant differences in participants' sketching scores based on the three VEs. Specifically, again, sketching score was higher with the MixedVE than with the Abstract ($p < .05$, d = 0.13) and the Realistic VEs ($p < .001$, d = 0.22). Among the interactions between the four independent variables, *VSM score x recall stage* F(1, 73) = 7.00, $p < .01$, $\eta_p^2 = .01$ and *age x visualization* F(2, 146) = 3.32, $p < .05$, $\eta_p^2 = .00$ were significant (Figure 4(e)). In *age x visualization* interaction; pairwise comparisons for each age group revealed that; younger participants' sketching scores were on average higher with the MixedVE than with the Abstract ($p < .01$, d = 0.21) and the Realistic VEs ($p < .001$, d = 0.34); whereas for the older participants, there were no significant differences in the sketching scores across the three visualization conditions. This finding demonstrates that the variability was too high among the older adults' performances in the VSM sample. Below we elaborate on this, and provide further interpretations of the observed results.

## Discussion

In this study, we hypothesized that with a custom-designed VE (MixedVE), we can improve spatial knowledge acquisition in tasks that involve perspective switching for users with differing abilities and age groups. Specifically, we evaluated the MixedVE against two baseline alternatives (AbstractVE, RealisticVE), and examined individual and group differences on spatial knowledge acquisition as acquired from a task requiring a perspective switch with these three VEs based on age, mental rotation abilities and visuospatial memory capacity.

As hypothesized, overall, our participants were able to produce more accurate and complete sketches after having worked with the MixedVE than with the other two VEs. These results support the potential use of the MixedVE as a memory training device in navigational tasks, for spatial knowledge acquisition that involves perspective switching.

While the MixedVE improves recall accuracy, the overall task success is somewhat low, reaching around 60%. This is possibly because of the difficulty of the task to mentally switch perspectives (Taylor & Tversky, 1996), despite the help the MixedVE provides. Alternatively, given how conspicuously well-documented the difficulty of this task is, one can interpret the success levels as somewhat high: Our participants watched the videos of the routes *only once*, and still were able to draw sketches at nearly 60% accuracy and completeness on average (including their performance a week later, which brings this number down as well). Although it is not straightforward to measure how much participants might have "guessed" in a task like drawing a sketch, we interpret these results as "above chance level" (as it was theoretically proposed earlier (e.g. Montello, 1998)).

If we interpret these results as success, the fact that the learning was *intentional* may have played a role in this success (Van Asselen et al., 2006). In a real-life memory training exercise, learning would be intentional too, and repetitions would be allowed; thus the accuracy would possibly improve further.

Visuospatial memory training is relevant in all ages, but clearly more relevant as people age. It is well-understood that aging negatively correlates with success in navigational learning (e.g. Muffato et al., 2016, 2017), especially as expressed in allocentric skills (Fricke & Bock, 2018). Our findings clearly confirm the relevance of aging as a factor in spatial knowledge acquisition with perspective switching tasks: Older participants had considerably less success in accurately sketching the route they followed in any of the VEs, and this was true in both the immediate and the delayed recall stages. While aging has well-documented detrimental effects on spatial memory, one must consider that there may also be "cohort effects": that is, the younger generations are exposed to an immense technological development, and their constant use of new technology may be altering younger people's cognition in comparison to older generations (Brown, 2000). As a consequence, the so-called "Y generation" may be more prone to learning via visual, linear, and even virtual means (Schofield & Honore, 2009). Such cohort differences may have contributed to the differences in our older and younger participants' route recall scores (obtained in a technology based virtual environment). Cohort differences, however, are difficult to control. A longitudinal study might offer interesting insights, but with the fast- and constantly-changing technology, it would present other problems; comparing their learning skills with the technology relevant for example 40 years ago may not provide the pure aging effect either, because they probably would have moved on too.

Furthermore, while aging is very relevant in examining navigational memory tasks, age-related decline in visuospatial abilities and/or memory capacity can vary based on individual and group differences. On this topic, our correlation analyses (among all examined factors) with a focus on participants' scores on the MRT and VSM tests revealed interesting patterns.

The analyses based on the MRT sample indirectly suggests that the high MRT group did better than the low MRT group with the AbstractVE both in immediate and delayed recall stages (i.e. there was no significant interactions between *MRT score* x *recall stage* x *visualization*). On the one hand, it is plausible that high-MRT group would do better with AbstractVE because the MRT measures mental rotation ability in the absence of meaningful visual cues (the MRT features abstract cube drawings), and among our visualizations, the AbstractVE is the most similar to that. On the other hand, one can also take the opposite view, considering that the task heavily relied on mental rotation (perspective switch) and the MRT is designed to measure mental rotation. From this point of view, we expected to see that the high MRT group would do well with the sketching task irrespective of the visualization type. It is possible that the added (photographic) visual cues would assist the low MRT participants (thus, they "catch up" with the others), when the visual cues were present: as in a "less fit" person might do similarly well on an e-bike as fitter cyclists, because the "aid" would remove the differences). Such speculations would lend themselves well for further testing in the future.

Furthermore, the MRT analysis revealed an interaction between *age x recall stage x MRT score*. This interaction effect points to a difference in the forgetting rates: high-MRT younger participants did really well a week later (they did not seem to forget much at all), while the high-MRT older participants did not do very well after a week has passed (though note that forgetting rates did not differ for the two age groups for low-MRT participants) (Figure3(e)). Seemingly, having a high MRT relative to other older participants does not mean much for the ability to retain the acquired spatial knowledge for the older participants. However, the high-MRT older group has scores in a similar range as the younger low MRT group; for which we see a similar decline in recall in the delayed stage. This suggests that there may be an upper limit in the amount of information older people can retain based on their spatial abilities, above which they may be out of capacity. In the MRT analyses, visualization type does not interact with the other variables; that is, the relative task success with the MixedVE is constant, irrespective of age, MRT scores or recall stage.

Another interesting observation in this study is that participants' MRT and VSM scores correlate, however, the outcomes of mixed-design ANOVAs are different when we examine the MRT and VSM samples separately. We believe this difference is (at least partly) due to changes in the sample after removing the median scores in each group.

High VSM participants performed consistently better in the sketching task across all visualization types, suggesting the VSM test might be able to predict sketching performance regardless of whether photographic/visual cues exist or not on the "base maps".

Interestingly, in the VSM sample, the main effect of *age* was non-significant, implying that age-related decline in the VSM abilities is *different* to the age-related decline in the MRT abilities. Indeed, the VSM test measures at least partially the *visual* memory, and it is previously documented that visual memory might be "spared" during healthy aging (Sekuler, Kahana, McLaughlin, Golomb, & Wingfield, 2005). Furthermore, in this analysis, *recall stage x VSM score* and *visualization type x age* interacted. Recall stage x VSM score interaction suggests that the visuospatial memory capacity plays an important role in the formation of a long-term memory of the spatial configuration irrespective of visualization type. This observation contributes to our understanding of the long-term retention of spatial knowledge where perspective switching is involved. An earlier study demonstrated a gender effect (in favor of female participants) for delayed retention of survey knowledge (Witmer et al., 2002), now we see that VSM abilities of the participants may have played a role too.

The *visualization x age* interaction points to MixedVE's stronger beneficial effects for the younger participants than the older. In the case of the older participants, perhaps a "floor effect" is present, that is, overall the sketching task, especially of a route requiring multiple orientation changes (Yamamoto et al., 2018), is too difficult for them, and MixedVE's slight assistance does not suffice in this case (Moffat, 2001; Wolbers et al., 2014). This interpretation is also in line with our qualitative observations. Especially in the "delayed recall" session (~one week later), many of our older participants expressed great difficulty, and some gave up on the task.

In summary, our findings clearly confirm that spatial knowledge acquisition that involves perspective switching is a cognitively challenging task, and overall, the MixedVE makes it somewhat easier. We also have learned that as important as the visualization design is, individual and group differences *must be* considered. Based on our findings, age and visuospatial memory capacity are clearly important factors in this context. In the mid- to long-term, these observations might be useful to personalize visualizations to better fit to an individual's abilities (i.e. to create personalized (Nivala & Sarjakoski, 2005; Zipf, 2002) "memory training devices").

## Conclusions and future work

In this paper, we provided new insights into the importance of addressing first of all the effect of aging, but also the individual differences in cognitive abilities (not only in terms of spatial abilities as measured by the MRT, but also of memory capacity as measured by the VSM test) in spatial knowledge acquisition in tasks that involve perspective switching when using different VEs. We gained deeper insights into the importance of visualization designs for navigational recall in general, and spatial knowledge acquisition where perspective switching is present in particular. We believe this study contributes to a better understanding of visualization design on spatial learning. Our results further help pave the way toward guidelines for designing (eventually personalized) VEs, also optimized for tasks that involve perspective switching. Such VEs can assist their users in learning a route, navigating more effectively and training their visuospatial memory both for short-term performance in spatial learning, and for long-term retention of the acquired knowledge. After these observations, our thoughts for future experimentation evolve around:

- Considering the implications of acquiring the spatial knowledge from the "reverse" perspective switch, that is encoding from a 2D view point (map reading) and decoding in a VE from a first-person perspective (i.e. wayfinding) under similar conditions as in our experiment.
- Understanding how locomotion affects learning for the different groups. Active vs. passive

involvement is known to have an effect on people (Appleyard, 1970; Chrastil & Warren, 2012). Understanding how active involvement might affect different age and ability groups can provide a more detailed reasoning as to how we should train people to achieve their best.
- How taking the route of interest more than once could affect spatial knowledge acquisition that involves perspective switching with the MixedVE as opposed to other VEs. We could then provide a benchmark as to which number of trials is the optimum for acquiring spatial knowledge.
- Decoupling age and MRT/VSM abilities. By pre-screening participants for their MRT/VSM scores, one can recruit similar numbers of people with higher and lower spatial abilities in each age group, and acquire a deeper understanding of the link between them.

Overall, based on observations we shared in this paper, we believe that individual and group differences such as age and abilities are very important to examine along with visualization design; and studies such as ours offer insights toward customized, and eventually personalized, visuospatial information displays which would facilitate route learning (as well as other learning) and potentially used for improving everyone's spatial memory.

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