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Individual differences in virtual reality: Are spatial presence and spatial ability linked?

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Abstract: One aim of virtual reality technology is to immerse the user in a digital environment that is distinct from physical reality. Feeling spatially located in this digital environment is central to the experience, and is more formally known as spatial presence. Experiences of spatial presence differ between individuals; prominent theories assume that these differences may, in part, be explained by differences in more general spatial abilities. Whilst there is some support for this claim with desktop systems there is currently no direct empirical evidence to support this with more immersive technologies such as Head Mounted Displays (HMDs). In this study participants completed three different measures of spatial ability before experiencing two virtual environments. These measures included: a self-report of visuospatial imagery; the mental rotations test; and a test of topographical memory. After completing the measures, participants briefly experienced a virtual city and a virtual train ride through a HMD. The user's head movements were tracked and visual displays were updated to give the sense of a full 360^{o} environment. After each experience the participants reported how present they felt and the extent to which they had a mental model of the environment. Self-reports of imagery were positively correlated with reports of spatial presence, consistent with previous literature. However, spatial presence was not related to performance on either of the more objective tests. Whilst this provides confirmatory evidence that self-reports of imagery can predict presence it is still unclear which more basic spatial abilities, if any, could underlie this relationship.

Keywords: Presence, Spatial Presence, Immersive Virtual Reality**,** Head Mounted Display, Spatial Cognition, Cognition

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1.0 Introduction

Presenting a digital environment through a head-mounted display (HMD) can make a user feel like they are physically located in a different place (e.g. Minksy 1980; Steuer 1992). This illusory sense of being spatially located within the digital environment is commonly referred to as physical presence (e.g. Lee 2004) or spatial presence (e.g. Lombard & Ditton 1997). Here we are concerned with the narrow definition of spatial presence as the feeling of being spatially located in the mediated space. The extent to which someone experiences this sense of location within a digital environment varies between individuals. These differences may relate to both technical variables (see Cummings & Bailenson 2015) and characteristics of the individual (see Ling et al. 2013). Central to several theoretical accounts is the basic assumption that spatial presence will, in part, be determined by how efficiently we mentally process the spatial relations within the environment. This assumption has been addressed most directly by the process model of spatial presence proposed by Wirth et al. (2007).

Wirth et al.'s (2007) process model of spatial presence consists of two levels. The first level involves using spatial information to form a 'mental model' of the situation ("is this stimulus a space? If yes, what kind of space is it?"). The theory proposes that this 'mental model' is then developed, at the second level, through confirmation of a specific perceptual hypothesis ("am I located in this space?"). An affirmative response to this specific perceptual hypothesis is thought to lead to a sense of spatial presence. A range of variables are hypothesised to influence this process including both technological features and user characteristics. Significantly, it is assumed that individuals who can process spatial arrangements effectively will find it easier to create a 'mental model' of the spatial environment. It is subsequently proposed that the easier it is to create this mental model the more likely someone is to positively affirm the perceptual hypothesis posed at the second level ("am I located in this space?"). An assumption within the literature (e.g. Wirth et al., 2007) is therefore that spatial abilities will be highly related to experiencing spatial presence. Spatial visual imagery in particular is identified as potentially important.

Whilst differences in spatial abilities *could* be related to spatial presence the evidence is far from conclusive. This link within the process model of spatial presence (Wirth et al. 2007) has been primarily supported using evidence from desktop based systems, and has focused upon the specific ability to create visuospatial images (mental imagery). For example, Hofer et al. (2012) pooled data across three studies which all used the same desktop virtual learning environment. In these instances the measure of spatial ability consisted of a self-report questionnaire regarding aspects of mental imagery. These included items such as "When I read a text, I can usually easily imagine the arrangements of the objects described" and "When someone describes a space to me, it's usually very easy for me to imagine it clearly.". In addition to subjective reports of imagery ability, subjective reports of spatial presence were collected along with reports on the extent to which a spatial situation model had been formed. Consistent with the process model (Wirth et al. 2007) imagery was related to the construction of a 'spatial situation model' which in turn was related to spatial presence. Hartmann et al. (2016) report similar data in a validation study for a shortened measure of spatial presence. In this case, direct correlations are reported between imagery and presence. There is therefore some evidence for this link when using virtual environments on desktop systems. However, the evidence is much less clear when more perceptually immersive systems have been used.

Unlike research with desktop systems, research with HMDs has failed to demonstrate the predicted relationship between spatial presence and spatial ability (Alsina-Jurnet & Gutiérrez-Maldonado 2010; Ling et al. 2013). Alsina-Jurnet and Gutiérrez-Maldonado (2010) investigated a range of measures that may predict individual differences in experiences of presence. Amongst other measures spatial intelligence was indexed by using a mental rotation test. Participants then experienced a series of virtual environments that included a typical student bedroom, metro journey, and university building. These environments were displayed to the participants using a HMD with self-reports of presence taken after the experiences. The measure of spatial intelligence was related to general reports of presence in these environments, however, correlations were only found in a high test anxiety group. Furthermore, no correlation was reported between spatial intelligence and the specific measure of spatial presence. The relationship was instead explained through measures of involvement, realism and the general sense of 'being there'. Consistent with this null result, Ling et al. (2013) also failed to find a correlation between spatial intelligence and spatial presence using both a HMD and a desktop system to present virtual environments. Again, spatial intelligence was indexed using a mental rotation test. The evidence thus far has failed to find a relationship when using more perceptually immersive systems. This is contrary to the assumptions of the process model of spatial presence (Wirth et al. 2007) and is seemingly inconsistent with the evidence available using some desktop systems (Hofer et al. 2012; Hartmann et al. 2016).

These mixed findings could potentially be explained by at least three key differences between the studies. One aspect worthy of attention is the use of different mediums. It is possible that spatial ability may be more important with desktop systems as greater cognitive effort and interpretation is required, depending on the cues available. HMDs may, by their very nature, offer sufficient spatial cues that differences in spatial ability would not overly affect the presence experience. However, the mediums are also confounded with the measures of spatial ability that are used. Where a relationship has been demonstrated with desktop systems the measure of spatial ability has been a general self-report measure of visuospatial imagery. By contrast, where a relationship has not been demonstrated with HMDs the measures have been tests of mental rotation (an alternative test of spatial visual imagery). Finally, the mixed results could also be explained by the use of very different simulations across different research groups.

The first aim of the current research was to ascertain whether a relationship between spatial ability and spatial presence can be demonstrated using a HMD. This is important because whilst the process model (Wirth et al. 2007) might extend across both desktop systems and HMDs there is no empirical evidence to support this assumption in terms of this relationship, and there are reports of being unable to find such evidence when looked for (Alsina-Jurnet & Gutiérrez-Maldonado 2010; Ling et al. 2013).

The second aim of the research is to directly compare the two measures which have been used previously to try to establish a relationship between spatial ability and spatial presence: mental rotation tests; and self-reports of imagery. It is currently unclear if the mixed findings are due to the use of these different measures to index spatial ability, or something else.

A supplementary aim here was to investigate the potential relevance of a more theoretically driven measure of spatial ability. Thus far the focus has been upon mental imagery but this represents a narrow area within spatial cognition. A measure of topographical memory was therefore also included here. Topographical memory refers broadly to memory for a viewpoint independent representation of larger environmental relations. There is therefore considerable overlap between the concept of topographical memory and Wirth et al.'s (2007) 'spatial situation model'. Central to both of these is a flexible and viewpoint independent mental representation of the spatial relations in the environment. The assessment of topographical memory, as an additional measure, is therefore theoretically driven. It was hypothesised that such a measure may act as a more reliable predictor of spatial presence than either of the two used thus far in the literature. This research question was exploratory in nature given that such a measure has not been used previously in this context.

Finally, the extent to which any relationship might be simulation specific was assessed. Here we distinguished between actively navigating around a virtual environment (a virtual city) and a more passive experience that also contained motion (riding an underground train/metro). Both simulations came from the same program so had similar visual appearances, and similar technical demands.

In the current study participants experienced both virtual environments using virtual reality technology (a HMD). Beforehand three different measures of spatial ability were taken: a mental rotation test; a questionnaire on visuospatial imagery; and a test of topographical memory. For consistency with the process model of spatial presence (Wirth et al. 2007), participants were also asked questions regarding the extent to which they could visualise the spatial relations within each virtual environment (the spatial situation model) alongside the extent to which they felt located in the environment. If the assumptions of the process model (Wirth et al. 2007) are correct then we would not only expect positive relationships between the measures of mental imagery and spatial presence, but also positive relationships with the ability to visualise the environment they were just presented with (their 'spatial situation model'). These should be independent of the fact that a HMD is being used, and should be replicated across both simulations.

2.0 Methods

All participants in this research provided written consent and the research was conducted in line with the principles of the Declaration of Helsinki. The study was approved by the Faculty of Health and Life Sciences Research Ethics Committee at York Saint John University (MC/21/01/15/MC).

2.1 Participants

A sample of 53 participants was recruited from the York St John University staff and student community on an opportunistic basis. A minimum sample size of 47 was considered appropriate using calculations from Bland (2000) with anticipated correlation coefficients of .5, alpha levels of .05, and beta levels of .2. Participants were excluded from participating if they had a known condition or health issue that interacted with the use of a HMD (e.g. feelings of nausea) or had experienced the simulations previously. Three participants were excluded on this basis leaving a total of 50; 28 of whom were male and 22 of whom were female with ages ranging from 18 to 53 years (M=23.28, SD=6.25).

2.2 Design

A within-participants design was used with two main outcome measures related to spatial presence (self-location; mental model) and three main predictor variables related to spatial ability (visuospatial imagery report; mental rotations test; four mountains test). Demographic data was also gathered to control for age, gender and gaming experience, and simulator sickness was measured after each experience.

2.3 Materials and Equipment

2.3.1 Self-report Measures

An initial questionnaire was used to gather data on age, gender and general health. In line with Kennedy et al. (1993) general health was ascertained using two questions which required yes or no as an answer: are you currently unwell?; and do you consider yourself to be in a normal state of health? Gaming frequency was ascertained with the question “How often (approximately) do you currently play video games?”. The response options were: Daily; Weekly; Once a month; Once in 6 months; Once a year; Less than once a year; Never; Prefer not to say.

Statements regarding visuospatial imagery were also presented on this initial questionnaire. Participants were provided six statements from the six-item version of the visual spatial imagery scale from the MEC-SPQ (Vorderer et al. 2004). These statements reflected different scenarios in which visuospatial imagery is used in everyday life, and participants were asked to report the extent to which each statement applied to them. Statements included: when someone shows me a blueprint, I am able to imagine the space easily; and, when someone describes a space to me, it’s usually very easy for me to imagine it clearly. Participants responded on a scale of 1 to 5 where 1 was denoted as “I do not agree at all” and 5 was denoted as “I fully agree”.

A presence questionnaire was administered after each experience. This consisted of 8 statements that were adapted from the MEC-SPQ (Vorderer et al. 2004), four of which were the four item scale measuring self-location and four of which were the four item scale measuring the formation of a ‘spatial situation model’. There are a range of existing scales that could have been chosen to measure presence however, items from the MEC-SPQ (Vorderer et al. 2004) were chosen in this instance because, unlike the other scales, the items mapped directly on to the components of the underpinning theoretical model (Wirth et al. 2007). This was considered advantageous in drawing inferences from the data to the theory. Items regarding self-location included: I felt I was actually there in the virtual city; and, it was as though my true location had shifted into the virtual city. Items regarding the ‘mental model’ included: I was able to imagine the arrangement of the spaces of the virtual city very well; and, even now I still have a concrete mental image of the spatial environment. Participants responded on a visual scale of 1 to 5 where 1 was denoted as “I do not agree at all” and 5 was denoted as “I fully agree”.

Finally, a simulator sickness questionnaire was also administered after each experience (Kennedy et al. 1993). This questionnaire consists of a list of 16 symptoms and requires that participants indicate the extent to which the symptom is affecting them at that moment. The response scale consists of: none; slight; moderate; and severe. The items consist of two sub-scales covering nausea (e.g. general discomfort, sweating, etc.) and oculo-motor issues (e.g. eye strain, difficulty focusing, etc.).

2.3.2 Spatial Ability Tests

In keeping with previous research, a mental rotations test was administered (Alsina-Jurnet & Gutiérrez-Maldonado 2010; Ling et al. 2013) and the standardised test provided by Peters et al. (1995) was chosen for this purpose. This is a re-drawn version of a test developed by Vandenberg and Kuse (1978). The test consists of images of 3D block patterns. On each trial a participant is presented with five images horizontally. The image on the far left is separated from the other four images and acts as the target. Participants are required to identify which of the images to the right of the target image are rotated versions. Of the four comparison images only two are rotated versions of the target, and have been rotated around the vertical axis (see *Figure 1*). Two sets of 12 trials were administered using pen and paper, and were time-limited.

Fig. 1 Example stimuli from the mental rotations test. Reproduced from Peters M, Laeng B, Latham K, Jackson M, Zaiyouna R, Richardson C (1995) A redrawn Vandenberg and Kuse mental rotations test-different versions and factors that affect performance. Brain Cognition 28:39-58. Copyright © 1995 by Academic Press, Inc. Reproduced with permission.

The Four Mountains Test (FMT) was administered as a measure of topographical memory. The test was developed by Hartley et al. (2007) and requires participants to match a target image to a choice of four alternatives. A target image is shown initially for 10 seconds at which point it is removed from view and replaced with four alternatives in a 2x2 grid (see box A in *Figure 2*). These four alternatives are displayed for 20 seconds, during which time participants must indicate the matching image using a pen and a paper response sheet. All images are computer generated landscapes which contain four mountains (see box B in *Figure 2* for an example target image, and box C for an example test display). The target and the alternatives differ according to both viewpoint and non-spatial properties such as the lighting, cloud cover and vegetation. Four practice trials were provided with feedback as part of the instructions, and the main test consisted of 30 trials.

Fig. 2 Example stimuli from the Four Mountains Test. Reproduced from Hartley T, Harlow R (2012) An association between human hippocampal volume and topographical memory in healthy young adults. Front Hum Neurosci 31:6. Copyright © 2012 by Hartley and Harlow. Reproduced with permission.

2.3.3 Simulation and Hardware

An alpha version of the software PHOBOS was provided for use from PsyTech for the virtual environments (http://phobos.psychologicaltechnologies.com/). PHOBOS is described as an anxiety and phobia management virtual reality platform. Developed for research into specific phobias, it provides interactive 3D environments which can be freely navigated including a range of locations within a city context. These include city streets, a metro, a lift, the rooftop of a building etc . For the purposes of this study the city streets and the metro were used as two distinct environments. The city streets consisted of a central city square surrounded by tower blocks and populated by both a range of people and vehicles (see *Figure 3*) as well as corresponding environmental sounds (e.g. the sound of moving vehicles). The environment could be freely navigated using a handheld game controller, it was not possible to ‘die’, and people/vehicles navigated around the participant or stopped if appropriate.

Fig. 3 An example image taken from the city environment in the alpha version of PHOBOS (http://phobos.psychologicaltechnologies.com). Reproduced with permission.

The metro environment consisted of an underground train ride. Participants were able to navigate onto the train using a hand controller and the train contained a range of people of different ages and genders (see *Figure 4*) as well as corresponding environmental sounds (e.g. the sound of the train moving). Once boarded, the train moved forwards for a few minutes before arriving at another station. In keeping with the city environment, it was not possible to ‘die’, and people navigated around the participant or stopped if appropriate.

Fig. 4 An example image taken from the metro environment in the alpha version of PHOBOS (http://phobos.psychologicaltechnologies.com). Reproduced with permission.

The head-mounted display was an Oculus Rift DK2 with a resolution of 960x1080 pixels per eye, a 100^o field of view, and a 75Hz refresh rate. The HMD used low persistence organic light-emitting diodes, and provided both head tracking and positional tracking. The HMD was connected to an Alienware 17 laptop with a 4th Gen Intel(R) Core(TM) i7-4710MQ processor and NVIDIA(R) GeForce(R) GTX 880M graphics card. Movement within the virtual environment was controlled using a standard wireless XBOX 360 controller from Microsoft.

2.4 Procedure

After providing written informed consent, participants completed the initial questionnaire including the visuospatial imagery questionnaire. Participants then completed both the mental rotations test and four mountains test in a counterbalanced order. In both cases the tests were administered according to the standardised instructions provided.

On completion of the spatial ability tests participants were moved to an adjoining room to experience the virtual environments. Participants were seated in front of the HMD and laptop. The headset was configured for each participant making use of the hardware's settings utility. This took into consideration the participant's gender, height, ear to eye distance, eye to jaw distance and inter-pupillary distance. Participants were briefly allowed to experience the demo scene in the settings utility to ensure they were comfortable with the equipment and didn't experience any adverse effects. The demo scene consisted of a table with objects on it (e.g. desk lamp, paper, pencil etc.) against a blue grid background that extended to the horizon. The scene was unrelated to the test simulations used in the study and was experienced from a stationary position.

Once the HMD was appropriately configured participants experienced two different virtual environments, the order of which was counter-balanced across participants. These two environments consisted of some city streets and a journey on the metro (for more details see Materials and Equipment above). Before the city environment was experienced participants were provided with a picture of a male avatar and instructed to locate him within the city. The purpose was to engage the participant with an attention-demanding task that required active navigation of the environment. The avatar pictured was not featured in the environment so that the end of the experience was within the control of the researchers. Participants experienced this environment through the HMD, wearing a pair of headphones, and navigating the environment using the game controller. The environment was experienced for two minutes after which the headphones and headset were removed and participants were asked to complete the simulator sickness questionnaire and the presence questionnaire in that order. Before the train simulation, participants were instructed to board the train after it approached the platform, and ride it to the next platform before disembarking. In contrast to the city environment, the intention here was to provide a relatively passive task that required little navigation other than to board the train and did not explicitly require them to attend to any features within the environment. Overall, participants were in the environment for approximately one minute and again completed the simulator sickness questionnaire and presence questionnaire when the experience was over. Finally, participants were debriefed and were given the opportunity to ask any questions.

3.0 Results

Raw data were converted to aggregated scores for each of the measures in the following ways. Responses to the visuospatial imagery statements were summed to form a total score. This created a maximum possible score of 30 and a minimum possible score of 5: high scores are indicative of reporting good visuospatial imagery whilst low scores are indicative of reporting poor visuospatial imagery. The mental rotations test was scored according to the number of times that participants correctly identified both matches to the target on each trial, creating a total possible score of 24 and a minimum possible score of 0. The four mountains test was scored according to the number of times the participant correctly matched the target image to the correct alternative. This allowed for a maximum possible score of 30 and a minimum possible score of 0. Responses on the self-location scale and mental model scale were both summed to create a maximum possible score of 20 for each, and a minimum possible score of 5. Finally, scores on the two sub-scales of the SSQ were calculated by scoring each item on a four point scale (None = 0, Slight = 1, Moderate = 2, Severe = 3). The minimum possible score for each of the sub-scales was therefore 0 with a maximum possible score of 27 on the nausea sub-scale and 21 on the oculo-motor sub-scale. Means and standard deviations for the measures taken are shown in Table 1, in each case $N = 50$.

Table 1. Descriptive statistics for the measures taken.

	Measure	*Mean*	*Standard Deviation*
Spatial Processing	Imagery Report (out of 30)	20.34	4.55
	Mental Rotations Test (out of 24)	10.98	5.49
	Four Mountains Test (out of 30)	22.62	4.08

Spatial Presence	Self-Location: City (out of 20)	13.06	3.35
	Self-Location: Metro (out of 20)	13.46	3.52
	Mental Model: City (out of 20)	14.04	3.97
	Mental Model: Metro (out of 20)	15.82	3.08
Simulator Sickness	SSQ Nausea Sub-Scale: City (out of 27)	2.96	3.64
	SSQ Nausea Sub-Scale: Metro (out of 27)	2.39	3.17
	SSQ Oculomotor Sub-scale: City (out of 21)	3.02	3.09
	SSQ Oculomotor Sub-scale: Metro (out of 21)	2.16	2.39

Non-parametric zero-order correlations were calculated between the main outcome measures in both scenarios (mental model; self-location) and the control variables (age, gender and gaming frequency) to identify any relationships that required statistical control. Positive relationships were identified between reports of a mental model and gaming frequency in both the city environment ($r(50)= .41$, $p<.05$) and the metro environment ($r(50)= .48$, $p<.05$). The more frequently participants played video games the easier they found it to create a mental model of the environment. There were also negative relationships identified between reports of a mental model and age in both the city environment ($r(50)= -.36$, $p<.05$) and the metro environment ($r(50)= -.31$, $p<.05$). The younger the participants reported finding it easier to create a mental model of the environment. No further significant relationships were identified between the outcome measures and the control variables. It is worth noting that age and gaming frequency were not related in this sample ($r(50)= .24$, $p>.05$).

Given the above results, partial correlations were calculated between the outcome measures and the measures of spatial ability (visuospatial imagery report; mental rotations test; and four mountains test) controlling for both age and gaming frequency. The results of these analyses are presented in Table 2 (* denotes $p<.05$).

Table 2. Partial correlations between the outcome measures and the measures of spatial ability.

		Measure of spatial ability		
		Imagery report	*Mental rotations test*	*Four mountains test*
City scenario	*Mental model*	.43*	-.03	.13
	Self-location	.29*	-.01	.08
Metro scenario	*Mental model*	.39*	-.02	.13
	Self-location	.45*	.18	.17

As can be seen from the table, visuospatial imagery was positively correlated with the formation of a mental model and reports of self-location for both scenarios. No significant correlations were found between the outcome measures and either the mental rotations test or the four mountains test.

Zero-order correlations between the separate measures of spatial ability were also calculated to determine if performance on the measures were related to each other. Visuospatial imagery reports were positively correlated with scores on the mental rotations test ($r(50)= .35$, $p<.05$) and the four mountains test ($r(50)= .31$, $p<.05$).The mental rotations test and the four mountains test were not correlated with one another ($r(50)= .20$, $p>.05$).

4.0 Discussion

In the current study we compared three different measures of spatial ability and determined whether they were related to spatial presence in two different virtual environments presented through a HMD. Consistent with some of the previous literature, that makes use of desktop systems, differences in self-reported imagery ability were found to be related to spatial presence (e.g. Hartmann et al. 2016). The better the reported imagery ability the more spatially present participants felt. Consistent with the theoretical model of Wirth et al. (2007) this measure was also related to visualising the spatial relations within the environment (the 'spatial situation model'). These links have not previously been demonstrated using a HMD as the medium and provide preliminary support to some of the main assumptions of the process model (Wirth et al. 2007). This finding was replicated across two different simulations which varied the active participation involved in navigating the environment. In doing so it provides the first direct evidence, within this population, that individual differences in visuospatial imagery could potentially account for at least some of the variation in spatial presence whilst using a HMD. However, such a conclusion must be treated with considerable caution.

More objective tests of mental rotation and topographical memory were also used but did not demonstrate the same pattern of associations as the self-report measure. Importantly, both measures *were* related to participant's self-reports of imagery ability. The self-report measure and the more objective tests therefore shared some common variance. Participants that were better at mental rotation, or demonstrated better topographical memory, also reported better imagery ability in general. However, neither objective test was found to be related to spatial presence; this common variance shared with self-reports of imagery ability did not extend to predicting spatial presence. It is therefore likely that the mixed findings in the current literature may be attributable to the measure of spatial ability used, rather than differences in the medium or simulation. Importantly, this casts some doubt on the proposition that spatial abilities *per se* are related to spatial presence.

Thus far, the available evidence has only ever reported a relationship between spatial presence and self-reports of imagery (Hartmann et al. 2016), and never with more objective tests (Alsina-Jurnet & Gutiérrez-Maldonado 2010; Ling et al. 2013). As noted in the introduction, this has been confounded by the use of desktop systems with self-report measures, and HMDs with ability tests. The research reported here provides the first direct test of both measures using the same environments within a HMD. The findings are clear that the self-report measure was related to spatial presence but the more objective tests were not. Before it can be claimed that spatial ability, or at a minimum spatial imagery, is related to presence in a broader theoretical sense it is paramount that this can be presented with a more objective measure than self-report. The evidence available from this study, and within the literature, continues to fail to demonstrate such a relationship.

Null findings should of course be treated tentatively and potential limitations need to be carefully considered. One potential limitation to this study is the sample size (n=50). The sample was sufficiently large to identify a range of statistical relationships between the variables investigated. Importantly, the sample size was big enough to identify a relationship between presence and imagery, as well as relationships between imagery and the other tests of spatial ability. All of these associations were expected and are entirely consistent with the related theoretical perspectives. Where the sample size was not sufficient was to identify a relationship between the objective test of processing and presence. The absence of such relationships with the mental rotation test in particular is consistent with the null findings in the previous literature which made use of larger sample sizes (Alsina-Jurnet & Gutiérrez-Maldonado 2010; Ling et al. 2013). That these previous studies used more objective tests of spatial ability provides support for the assumption that sample size alone is not responsible for the null findings reported here.

Furthermore, it is possible that the conclusions are specific to the environments used, and the tasks participants completed. It is somewhat unavoidable that any research in this vein may be limited by some specific aspect of the environments used given that all possible environments can never be tested in any single study (or series of studies). Here we varied the task such that participants actively explored a virtual city in one scenario, whilst relatively passively experiencing a train ride in another. The results were consistent across both scenarios indicating that they generalise across at least these two different experiences. That the relationships identified were also consistent with findings using desktop systems (Hartmann et al. 2016) and the process model in general (Wirth et al. 2007) adds further support to the possibility that the results reported here are unlikely to be environment specific. Instead, it appears to be the case that there is something special about self-reports of imagery and spatial presence which is distinct from at least some traditional tests of spatial ability.

Finally, the specific measures of spatial ability used also require careful consideration. In this instance the measures were intentionally chosen to be consistent with the existing literature in an attempt to investigate the mixed findings. The questionnaires were taken directly from evidence that spatial presence and spatial ability were related in virtual environments (Hartmann et al. 2006) whilst the mental rotation test was chosen as it had been used consistently in research with HMDs that failed to demonstrate this link (Alsina-Jurnet & Gutiérrez-Maldonado 2010; Ling et al. 2013). In future research it will be important to adopt a more differentiated view of spatial ability and investigate a range of alternative measures. The next important step is to determine which, if any, aspects of spatial ability best predict presence. An initial attempt to explore this question was made here through the use of a topographical memory test. Given the significant conceptual overlap between Wirth et al.'s (2007) notion of a spatial situation model and topographical memory the lack of a relationship was surprising. It is worth noting again that there was shared variance between the test of topographical memory and the self-reports of visuospatial imagery. Future research could usefully explore what these common components are and their relationship with presence. In doing so it will be important to carefully consider finer distinctions in the cognitive processes which underpin visuospatial imagery. For example, Kosslyn (1994) identifies dissociable processes of: image generation; image maintenance; image inspection; and image transformation. It will be important to explore which, if any, of these components drives the relationship between imagery ability and spatial presence.

Overall, this study has provided the first clear evidence that differences in self-reported imagery ability can predict reports of spatial presence when experiencing a virtual environment through a HMD. This provides confirmatory evidence and some support for the process model of spatial presence (Wirth et al 2007). However, this study also tested for associations with more objective tests of spatial ability: mental rotation and topographical memory. No evidence was found to support the importance of these for spatial presence. These findings are inconsistent with general expectations given the process model (Wirth et al. 2007), and caution needs to be exercised in assuming that spatial ability and spatial presence are linked at a broader theoretical level. Self-report measures provide some indication that visuospatial imagery may be important but what the most important aspects are, and how to measure them, are questions that require further attention.

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