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Spatial ability at two scales of representation: A meta-analysis

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ABSTRACT

The primary objective of this meta-analysis is to examine the relationship between small-scale and large-scale spatial abilities. The secondary objective is to investigate whether gender and age moderates this relationship. Peer-reviewed journal articles published between 1985 and 2014 were retrieved through an extensive literature search using different combinations of the keywords navigation, mental rotation, small-scale space, large-scale space, spatial ability, and way-finding. Twenty-seven studies were initially identified. Fifteen studies were included in the final analysis. Both Q statistic and I^2 suggest that the reported effect sizes, i.e., the associations between small-scale and large-scale spatial abilities, are heterogeneous. Therefore, a random effects model was fit. The multiple regression model explains a significant amount of the variance of the effect sizes. Overall, results from this meta-analysis suggest that small-scale and large-scale spatial abilities are best characterized as separate abilities. Regarding the moderators, whereas age effect is statistically significant, gender effect is not.

1. Introduction

High spatial ability is linked to success in science technology, engineering, and mathematically-related careers (STEM) (Webb, Lubinski, & Benbow, 2007). Spatial ability is also crucial to everyday problem solving (*Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006). Spatial ability has been defined as the ability to understand the relationships among different positions in space or imagined movements of two- and three-dimensional objects (Clements, 1999). Small-scale and large-scale spatial abilities are two main categories of spatial abilities that emerged from the literature (Jansen, 2009). Tasks assessing small-scale spatial ability typically involve mentally rotating small objects along the objects' central axis, i.e., the allocentric frame of reference. Tasks assessing large-scale spatial ability typically involve mental rotation along body axis, i.e., the egocentric frame of reference. *Hegarty et al. (2006) argue that small-scale and large-scale spatial abilities are dissociated. The authors cited the individual differences literature, which showed that the correlation between performances on the two categories of spatial tasks is close to zero. Neuroscience data reveals that small- and large-scale spatial abilities rely on distinct neural substrates (Kosslyn & Thompson, 2003; Morris & Parslow, 2004). Furthermore, behavioral data shows that there are higher correlations among subcategories of small-scale tasks (e.g., mental rotation, spatial perception, and spatial visualization tasks, which are three subcategories of small-scale spatial ability tasks, see Linn & Petersen, 1985) than across small- and large-scale spatial ability tasks (and the same for large-scale spatial ability tasks). Thus, together, the brain and behavioral data suggest dissociation between small- and large-scale spatial abilities.

1.1. Small-scale spatial ability

The fundamental distinction between small-scale and large-scale spatial abilities rests on the different frames of reference involved when solving the two types of spatial problems (*Malinowski, 2001). As mentioned previously, solving small-scale spatial ability tasks involves allocentric spatial transformation. Small-scale spatial ability has also been referred to as "object-based transformation" (see *Zacks, Mires, Tversky, & Hazeltine, 2000); "mental rotation" (Blajenkova, Motes, & Kozhevnikov, 2005); "object manipulation" (*Kozhevnikov & Hegarty, 2001); and "psychometric spatial ability" (*Allen, Kirasic, Dobson, & Long, 1996).

1.2. Large-scale spatial ability

Large-scale spatial ability tasks typically involve egocentric spatial transformation (*Hegarty & Waller, 2004). During egocentric spatial transformation, viewer's perspective changes with respect to the larger environment, but the spatial relationships among individual objects do not change. Environmental navigation is a type of large-scale spatial ability (*Kozhevnikov, Motes, Rasch, & Blajenkova, 2006). During environmental navigation, spatial relationships among landmarks cannot typically be apprehended from a single vantage point (*Hegarty & Waller, 2004; *Quaiser-Pohl, Lehmann, & Eid, 2004). Instead, like with

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other large-scale spatial ability tasks, participants are to engage in egocentric spatial transformations in order to apprehend the large-scale environment as a whole. Other terms that have been used to refer to large-scale spatial ability are “egocentric perspective transformation” (*Zacks et al., 2000); “sense of direction” (De Beni, Pazzaglia, & Gardini, 2006); “spatial orientation” (*Kozhevnikov & Hegarty, 2001); “perspective taking” (*Hegarty & Waller, 2004); and “way-finding” (*Malinowski, 2001).

1.3. Dissociation between small-scale and large-scale spatial abilities

Citing neuroscience, experimental, and psychometric studies, *Hegarty et al. (2006) concluded that small-scale and large-scale spatial abilities are best characterized as dissociated. Evidence supporting the distinction between small-scale and large-scale spatial abilities comes from both brain and behavioral studies (*Hegarty et al., 2006). Kosslyn and Thompson (2003) and Morris and Parslow (2004), for instance, found that solving small-scale and large-scale spatial ability tasks activate distinct parts of the brain. Performing small-scale spatial ability tasks (e.g., mental rotation) tends to activate parietal lobes (see Kosslyn & Thompson, 2003). On the other hand, performing large-scale spatial ability tasks (e.g., environmental navigation) tends to activate the hippocampus (Gogos et al., 2010; Hugdahl, Thomsen, & Ersland, 2006) and surrounding regions in the medial temporal lobes (e.g., Morris & Parslow, 2004).

Behavioral findings are generally consistent with neuropsychological evidence, which highlighted the dissociation between small-scale and large-scale spatial abilities (e.g., *Hegarty & Waller, 2004; *Hegarty et al., 2006). Performing both categories of spatial tasks requires the ability to maintain a high quality internal representation of spatial relationships. However, during encoding, learning large-scale spatial layouts may involve other sensory inputs in addition to vision (e.g., proprioception); solving small-scale spatial problems typically involves vision alone. Likewise, solving small-scale spatial problems typically requires allocentric spatial transformation, whereas solving large-scale spatial problems typically requires egocentric spatial transformation. Thus, there are both brain and behavioral bases for the dissociation between small-scale and large-scale spatial abilities. While there is evidence for the dissociation between small-scale and large-scale spatial abilities, the degree of dissociation between the two categories of spatial abilities are inconsistent across different studies. We believe that a systematic review (e.g., meta-analysis) of the existing psychometric studies on this topic could shed light on the degree of dissociation between small-scale and large-scale spatial abilities. Because the relationship between small-scale and large-scale spatial abilities may be moderated by gender and age, the second objective of this meta-analysis is to explore whether the relationship between small-scale and large-scale spatial abilities varies across different levels of the two moderators, gender and age.

1.4. Moderators: gender and age

In reviewing the literature, the magnitude of the association between small-scale and large-scale spatial abilities appears to vary by the characteristics of the samples, e.g., gender and age distributions. *Quaiser-Pohl et al. (2004) reported a Pearson correlation of 0.11 between small-scale and large-scale spatial abilities for elementary school children with an average age of 9.91 years. In another study that used young adults as research participants, the association between small-scale and large-scale spatial abilities approached 0.30 (*Hegarty et al., 2006). Results from these two studies suggest that the magnitude of the association between small-scale and large-scale spatial abilities may be sensitive to the age characteristics of the samples. Therefore, in this meta-analysis, age was treated as a potential moderator.

Gender is typically a factor to consider in behavioral studies of individual differences in cognitive abilities and spatial abilities in particular. There is evidence that males and females recruit different neural networks even when processing identical visuospatial information (e.g., Hugdahl et al., 2006). Therefore, in this meta-analysis, gender was treated as the second potential moderator.

The following research questions guided this meta-analysis:

1. What is the strength of the association between small-scale spatial ability and large-scale spatial abilities?
2. Does gender moderate the strength of the association between small-scale and large-scale spatial abilities?
3. Does age moderate the strength of the association between small-scale and large-scale spatial abilities?

2. Method

2.1. Literature search

The methodology, analysis, and reporting of the findings in this study is guided by the PRISMA protocol. The PRISMA protocol is a 27-item checklist developed by Moher, Liberati, Tetzlaff, and Altman (2009, see also Liberati et al., 2009) to guide the reporting of systematic review and meta-analysis. Studies published from 1985 to 2014 were reviewed using different combinations of the following keywords: navigation, mental rotation, small-scale space, large-scale space, spatial ability, and way-finding. Year 1985 was used as the starting year because empirical studies published prior to those of Linn and Petersen (1985) were not consistent in the usage of the terms spatial perception, mental rotation, and spatial visualization. Keywords were entered into the following electronic databases: Academic Search Complete, Google Scholar, PsycINFO, ScienceDirect, SCOPUS, and Web of Sciences. The last date of literature search was on May 26, 2014. The references retrieved through the electronic databases were carefully reviewed. The criteria for the inclusion and exclusion of studies for this meta-analysis were as follows:

1. *Publication*: Only empirical studies published in peer-reviewed journals were included. Dissertations, conference publications, or other technical research reports were not included. This is because those types of publications tend to not go through a rigorous review and, therefore, may compromise the quality of the study.
2. *Sufficient statistics provided*: Studies that did not report basic statistics such as means, standard deviations, t-values, F-values, or p-values that would allow the computations of effect size expressed as a Pearson r were not included. Only studies that either reported Pearson r or those other statistics that would allow the computation of Pearson r were included.
3. *Indirectly related*: Studies that focused either exclusively on small-scale or large-scale spatial ability, or were conceptual in nature were considered to be indirectly related and, therefore, were not included.
4. *Language*: Only studies published in English were included.

2.2. Study characteristics and calculation of effect sizes

Fifteen empirical studies representing 13,333 participants were included. The results reported in these studies permitted the calculation of 91 effect sizes. Most studies reported multiple effect sizes (the number of effect sizes per study ranged from 2 to 18, with a mean of 9.92). To account for the possible nesting effect, variables that could affect the association between small-scale and large-scale spatial abilities, e.g., age and gender, were treated as moderators. Cognitive skills tend to stabilize in adolescence. To create two non-overlapping age groups, age 18 was used as a cut-off value, i.e., children (<18 years) and adults (≥18 years). To analyze gender, the gender distribution of the samples was divided at 55%. This resulted in three categories: 1) females predominated (females ≥ 55%); 2) balanced (45% < males < 55%); 3) males predominated (males ≥ 55%). The number of studies classified