Intelligence 47 (2014) 54–62

Contents lists available at ScienceDirect

Intelligence

Etiological distinction of working memory components in relation to mathematics

Sarah L. Lukowski [a,*], Brooke Soden [a], Sara A. Hart [b], Lee A. Thompson [c], Yulia Kovas [d,e,f], Stephen A. Petrill [a]

[a] Department of Psychology, The Ohio State University, Columbus, OH 43210, USA
[b] Department of Psychology and the Florida Center for Reading Research, Florida State University, Tallahassee, FL 32306, USA
[c] Department of Psychological Sciences, Case Western Reserve University, Cleveland, OH 44106, USA
[d] Social, Genetic, and Developmental Psychiatry Research Centre, Institute of Psychiatry, London SE58AF, UK
[e] Laboratory for Cognitive Investigations and Behavioural Genetics, Tomsk State University, Russia
[f] Psychology Department, Goldsmiths, University of London, UK

ARTICLE INFO

Article history:
Received 6 February 2014
Received in revised form 26 August 2014
Accepted 1 September 2014
Available online 29 September 2014

Keywords:
Working memory
Mathematics
Behavioral genetics
School-aged children

ABSTRACT

Working memory has been consistently associated with mathematics achievement, although the etiology of these relations remains poorly understood. The present study examined the genetic and environmental underpinnings of math story problem solving, timed calculation, and untimed calculation alongside working memory components in 12-year-old monozygotic ($n = 105$) and same-sex dizygotic ($n = 143$) twin pairs. Results indicated significant phenotypic correlation between each working memory component and all mathematics outcomes ($r = 0.18–0.33$). Additive genetic influences shared between the visuo-spatial sketchpad and mathematics achievement were significant, accounting for roughly 89% of the observed correlation. In addition, genetic covariance was found between the phonological loop and math story problem solving. In contrast, despite there being a significant observed relationship between phonological loop and timed and untimed calculations, there was no significant genetic or environmental covariance between the phonological loop and timed or untimed calculation skills. Further analyses indicated that genetic overlap between the visuo-spatial sketchpad and math story problem solving and math fluency was distinct from general genetic factors, whereas *g*, phonological loop, and mathematics shared generalist genes. Thus, although each working memory component was related to mathematics, the etiology of their relationships may be distinct.

1. Introduction

Mathematics achievement is a critical gateway for individual educational attainment and socioeconomic status, as well as for national prosperity (National Mathematics Advisory Panel, 2008; Ritchie & Bates, 2013). Given that mathematics disability affects 5–8% of the population (Geary, 2004), understanding and ameliorating mathematics difficulties has become a primary concern of many researchers, educators, and governments. As a result, extensive research has examined the cognitive underpinnings of mathematics achievement across a wide array of mathematical skills. Within this broader literature, Baddeley's model of working memory has been particularly influential (for review see Raghubar, Barnes, & Hecht, 2010). Briefly, the model posits a central executive and two passive stores: the phonological loop and visuo-spatial sketchpad (Baddeley, 2001). The phonological loop processes short term verbal information, such as lists of digits or words, whereas the visuo-spatial sketchpad processes short term visual and spatial information, such as patterns or sequences of movements.

* Corresponding author.
E-mail address: lukowski.4@osu.edu (S.L. Lukowski).

http://dx.doi.org/10.1016/j.intell.2014.09.001
0160-2896/

The phonological loop has typically been assessed by utilizing lists of nonwords (Gathercole, Willis, Baddeley, & Emslie, 1994) or lists of digits, as featured in numerous intelligence test batteries, such as the Wechsler Intelligence Scale for Children (Wechsler, 2004). A key difference between the tasks is that digit span features words in the lexicon (Baddeley, Gathercole, & Papagno, 1998), though the two tasks are highly correlated with each other in middle childhood (Gathercole et al., 1994). While the phonological loop has been noted as particularly important to language development (Baddeley et al., 1998), its role in mathematical skills has also been examined. Numerous studies have established a relationship between the phonological loop and mathematics (Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007; Henry & MacLean, 2003; Koontz & Berch, 1996; Maybery & Do, 2003; Meyer, Salimpoor, Wu, Geary, & Menon, 2010; Passolunghi & Siegel, 2001; Rasmussen & Bisanz, 2005; Swanson & Beebe-Frankenberger, 2004). For example, Swanson and Beebe-Frankenberger (2004) found that short term phonological memory was a significant predictor of word problem solving, but not of math calculation ability. In general, studies have shown that when the phonological loop is a predictor of mathematics, the mathematics task requires more complex computations (for review see DeStefano & LeFevre, 2004; Raghubar et al., 2010), and that the phonological loop is not as robustly related to simple math computations or retrieval of factual mathematics knowledge. The phonological loop may also be particularly important for computations in which children rely on counting strategies (e.g. Geary, 1993; Hecht, 2002). In addition, children with math disability or at risk of math disability possess smaller phonological loop spans than typically developing children.

Other studies have shown a significant correlation between the visuo-spatial sketchpad and mathematics (Bull, Espy, & Wiebe, 2008; Geary et al., 2007; Henry & MacLean, 2003; Holmes & Adams, 2006; Kyttälä, 2008; Maybery & Do, 2003; Rasmussen & Bisanz, 2005; Reuhkala, 2001; Simmons, Willis, & Adams, 2012). Simmons et al. (2012) suggested that the visuo-spatial sketchpad, as measured by block recall, was a unique predictor of 5- to 8-year-old children's number writing and symbolic magnitude judgments. Likewise, Maybery and Do (2003) found that fixed spatial span was the best predictor of mathematics performance across three domains of mathematics: number, measurement, and space. In early adolescence Henry and MacLean (2003) suggested that visuo-spatial working memory predicted arithmetic reasoning. Moreover, visuo-spatial working memory has been found to be a predictor of mathematics in children that score in the top 3% on the mathematics portion of the Scholastic Aptitude Test (Dark & Benbow, 1991). Thus, across a wide range of ages and tasks there is a moderate and significant relationship between visuo-spatial sketchpad functioning and mathematics.

In parallel to the aforementioned literature, research has begun to elucidate the genetic and environmental underpinnings of both working memory components and mathematics. As is the case with most cognitive variables, this work has shown that working memory components are, in general, moderately heritable (Ando, Ono, & Wright, 2001; Luciano et al., 2001; Plomin, Pedersen, Lichtenstein, & McClearn, 1994; Polderman et al., 2006; Thapar, Petrill, & Thompson, 1994). Moreover, the genetic contributions to working memory, while associated with genetic influences on general cognitive ability, also are partially distinct from genetic factors influencing general cognitive ability (Ando et al., 2001; Luciano et al., 2001; Polderman et al., 2006). Shared environmental influences tend to be non-significant, whereas significant nonshared environmental influences have been indicated for components of working memory. In terms of mathematics, results suggest that additive genetic influences are significant across a variety of mathematics achievement measures (Alarcón, Knopik, & DeFries, 2000; Hart, Petrill, Thompson, & Plomin, 2009; Kovas, Harlaar, Petrill, & Plomin, 2005; Oliver et al., 2004; Thompson, Detterman, & Plomin, 1991). Mathematics appears to share genetic variance with reading and general cognitive ability, but also has unique additive genetic effects that are specific to math (Alarcón et al., 2000; Hart et al., 2009; Kovas et al., 2005). Additionally, mathematics has shared environmental influences (Hart et al., 2009; Petrill et al., 2012).

Taken together, though there is a growing body of evidence describing the relationship between working memory components and mathematics, the etiology of working memory components, and the etiology of mathematics achievement, these literatures are largely separate and little is known about the underlying etiology of working memory components in relation to mathematics. Therefore, one important unresolved issue is whether the underlying genetic and environmental etiologies of working memory components are associated with the genetic and environmental influences on mathematics. Both the visual–spatial sketchpad and the phonological loop are moderately correlated with measures of mathematics, but the factors that underlie these patterns of covariance may be distinct. Understanding whether individual differences in mathematics achievement and working memory components have common genetic and environmental influences provides evidence as to what may underlie these correlations and may influence how we address mathematics disabilities more broadly.

Thus, the purpose of the present study was to examine the genetic and environmental contributions to the relationship between working memory components and mathematics achievement using a twin design. Because the previous literature suggested significant additive genetic influences on both working memory and mathematics and established a link between visuo-spatial span and several mathematics tasks, we hypothesized that genetic influences associated with the visuo-spatial sketchpad would be generally associated with mathematics measures. Furthermore, we hypothesized that solving math story problems, but not timed calculation and untimed calculation, would have additive genetic overlap with phonological loop processing. Finally, given that previous univariate estimates of the factors influencing working memory have in general not provided evidence for significant shared environmental effects, it was predicted that mathematics would have shared environmental influences that are distinct from working memory components. Likewise, it was hypothesized that nonshared environmental influences would largely be distinct to each measure.

Within these bivariate relations it is possible that significant genetic or environmental etiological overlap between working memory components and mathematics is subsumed by general factors that account for variation between numerous cognitive domains (Plomin & Kovas, 2005). Therefore, it was also important to address the relationship between working memory and mathematics in the context of general cognitive