Neuropsychologia 101 (2017) 17–29

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Mental arithmetic in the bilingual brain: Language matters

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ARTICLE INFO

Keywords:
Mathematics
Neuroimaging
Bilingualism
Numerical cognition
Arithmetics

ABSTRACT

How do bilinguals solve arithmetic problems in each of their languages? We investigated this question by exploring the neural substrates of mental arithmetic in bilinguals. Critically, our population was composed of a homogeneous group of adults who were fluent in both of their instruction languages (i.e., German as first instruction language and French as second instruction language). Twenty bilinguals were scanned with fMRI (3 T) while performing mental arithmetic. Both simple and complex problems were presented to disentangle memory retrieval occuring in very simple problems from arithmetic computation occuring in more complex problems. In simple additions, the left temporal regions were more activated in German than in French, whereas no brain regions showed additional activity in the reverse constrast. Complex additions revealed the reverse pattern, since the activations of regions for French surpassed the same computations in German and the extra regions were located predominantly in occipital regions. Our results thus highlight that highly proficient bilinguals rely on differential activation patterns to solve simple and complex additions in each of their languages, suggesting different solving procedures. The present study confirms the critical role of language in arithmetic problem solving and provides novel insights into how highly proficient bilinguals solve arithmetic problems.

1. Introduction

While it is largely accepted that humans possess non-verbal core numerical abilities and basic arithmetic intuitions (Wynn, 1992; Feigenson et al., 2002), it is also becoming increasingly clear that language plays a critical role in numerical and mathematical thinking (Moeller et al., 2015; Van Rinsveld et al., 2016). Formal instruction is needed to acquire most exact arithmetic competencies and the acquisition of number words and their symbols is a prerequisite for accurate representation and manipulation of large numerical quantities (Gordon, 2004; Pica et al., 2004; Wynn, 1990). Consequently, some aspects of exact number processing remain under the influence of language long after exact number representation acquisition (see Göbel et al., 2011, for a review).

Given the importance of language for numerical processes, it appears crucial to study not only how the monolingual mastery of a specific language affects numerical cognition, but also how mastery of multiple languages impacts number processing and mathematical thinking. Nowadays, the language profiles of school children are indeed becoming increasingly complex, with bi- or multilingual learners being the norm rather than the exception in many places (Grosjean, 2010). While numerous behavioral experiments allowed us to gain valuable insights into performance differences and similarities between mono- and bilingual number processing and computation (e.g., Geary et al., 1993), corresponding neuroimaging studies are still rare (Lin et al., 2011; Wang et al., 2007; Venkatraman et al., 2006; for electrophysiological evidence see Martinez-Lincoln et al., 2015; and Salillas and Wicha, 2012). Especially fMRI studies are scarce and there are virtually no such studies investigating activation pattern in highly proficient balanced bilinguals. The present study aims to address this shortcoming by providing insights into the neural correlates of arithmetic problem solving in highly proficient bilinguals.

1.1. The triple code model of numerical cognition

According to the Triple Code Model (TCM), numbers can be

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http://dx.doi.org/10.1016/j.neuropsychologia.2017.05.009
Received 19 December 2016; Received in revised form 5 May 2017; Accepted 6 May 2017
Available online 08 May 2017
0028-3932/

represented in three different codes: an amodal code consisting of an abstract magnitude representation, a verbal code consisting of number words, and a visual-symbolic code consisting of Arabic digits. The magnitude representation of numbers can be accessed either through their verbal form in terms of number words or through their symbolic form in terms of Arabic digits (Dehaene, 1992). Ample neuroimaging evidence has corroborated this theoretical model as follows: Core representations of numbers (amodal code) were consistently reported to be located within the Intra-Parietal Sulci (IPS), while verbal and visuo-spatial processing were shown to rely on other parietal regions not specifically dedicated to numbers, namely the left Angular Gyrus (AG) and the Posterior-Superior Parietal Lobules (PSPL) respectively (e.g., Dehaene et al., 2003). More recently, Arsalidou and Taylor (2011) proposed an updated version of the TCM by suggesting the recruitement of a broader network of activations during numerical tasks involving amongst others working memory or long-term memory regions depending on the specific cognitive demand of the task. Moreover, the involvement of these broad networks in numerical cognition has been supported by brain imaging studies uncovering the structural connections between the typical TCM areas and other regions recurrently associated with numerical processing (Klein et al., 2014a).

In the case of arithmetic, the parietal regions described in the TCM appear to be active, but their relative activation strength varies as a function of the solving procedures. With learning and increasing expertise, problems are more frequently solved by means of retrieval from verbal memory. This leads to an increased activation within the left AG and/or hippocampus, parahippocampal and retrosplenial regions, as well as decreased activation within the IPS in both children and adults (Delazer et al., 2003; Grabner et al., 2009a; Ischebeck et al., 2006, Bloechle et al., 2016). In addition, arithmetic computation also activates broad cerebral networks involving frontal, temporal and subcortical regions, which underlie working memory and executive processes (see Dehaene et al., 2004 for a review; and see Arsalidou and Taylor, 2011 and Klein et al., 2014a for an updated version of the TCM). Since the adjusted TCM provides a well-recognized theoretical framework for the description of the neuronal activation pattern underlying numerical processing and arithmetic in typical monolingual individuals, we used this framework to comparatively describe the regions activated in bilingual individuals during mental arithmetic tasks.

1.2. The importance of language in arithmetic

While the existence of a language-dependent exact calculation system was proposed by numerous neuro-imaging studies (Dehaene et al., 1999; Cohen et al., 2000; Gruber et al., 2001; Stanescu-Cosson et al., 2000), the importance of language in arithmetic depends on a series of factors. One such factor is the type of operation. Namely, solving simple addition or multiplication problems relies more on verbally retrieved solutions than solving subtraction and division problems, probably because the former are more frequently learned and used in their verbal code (Lemer et al., 2003). Consequently, language should play a greater role in the former than in the latter. This assumption is coherent with many neuropsychological studies, which reported that preservation of language is more important for some operations (typically multiplications) than for others (typically subtractions). While subtractions are possible in case of lesions within the language areas but not in case of parietal lesions, the inverse is observed for multiplications (Basso et al., 2005; Baldo and Donkers, 2007; Cappelletti et al., 2001; Dehaene and Cohen, 1997; Delazer et al., 1999; Rossor et al., 1995). These dissociations suggest that different solving processes are engaged in multiplication and subtraction, relying relatively more on retrieval of verbally memorized arithmetic facts and mental manipulation of quantities respectively. Addition stands apart from this strict dissociation, because it relies on both verbal fact retrival and quantity manipulation (Dehaene et al., 2004). The current study will focus on addition in order to grasp the distinct role of language in these different solving processes within the same operation.

With respect to addition, it is important to separately examine the specific role played by language in each of the two classically distinguished arithmetic solving processes: retrieval of arithmetic facts and arithmetic computation. On the one hand, there are simple addition problems that are composed of two 1-digit operands (i.e., with addends smaller than 10). It is widely accepted that learning and practice of the latter lead to a direct retrieval of their solutions from verbal memory, where they are stored in the form of "arithmetic facts" (Ashcraft, 1992; McCloskey, 1992). On the other hand, more complex addition problems (i.e., with addends larger than 10) cannot be directly retrieved from memory and thus require the execution of mental computations. Importantly, these computations need working memory resources not only for their execution, but also for keeping intermediate results in memory and updating the final response (Ashcraft, 1995; Hitch, 1978). Such processes may rely on the phonological loop (see Baddeley, 1992; Logie et al., 1994; Fürst and Hitch, 2000; Imbo and LeFevre, 2010). Arithmetic fact retrieval and more complex computations have been shown to rely on two large but distinct brain networks involved in arithmetic problem solving (Klein et al., 2013). Taken together, these findings suggest that language plays a role in arithmetic problem solving in general and in additions at two levels: it enables the retrieval of arithmetic facts potentially represented within or retrieved from verbal long-term memory and it is also involved in complex arithmetic solving processes at least partially relying on verbal working memory components. Given this multifacetedness of addition, the present study was particularly interested in the activation pattern observed when highly proficient German-French bilinguals solve both simple and complex addition problems.

1.3. The role of language in bilingual arithmetic

Once it is established that language plays an important role in arithmetic problem solving, it is evident that one also needs to consider how the mastery of multiple languages affects these processes in bi- or multilingual subjects who master several languages. Behavioral research on bilinguals' arithmetic problem solving has pointed out an advantage for doing arithmetic in the first language (e.g., Marsh and Maki, 1976; Frenck-Mestre and Vaid, 1993) or at least in the language in which arithmetic is taught (e.g., Bernardo, 2001; Van Rinsveld et al., 2015). However, very fluent bilinguals seem to be able to retrieve arithmetic facts equally well in both of their languages (Campbell and Epp, 2004). Nevertheless, behavioral studies provide only limited information about the verbal nature of the processes engaged in mental arithmetic.

To obtain direct insights into the different brain regions (language-related vs. language-independent) underlying arithmetic problem solving in bilinguals, one needs to rely on neuro-imaging techniques such as fMRI. An fMRI study with Chinese-English bilinguals trained participants to solve mental arithmetic problems in one language (i.e. Chinese or English) and asked them to retrieve the solutions in both languages (Venkatraman et al., 2006). Bilinguals showed more activation within the left inferior frontal regions while retrieving the learned problems in the untrained than in the trained language. These findings suggest that some translation processes might be required to convert the fact from the trained into the untrained language. These results support Spelke and Tsivkin's (2001) conclusions that arithmetic facts are stored in a verbal format since they can be retrieved more easily in the language of learning.

However, even though training studies highlight the importance of language when learning new arithmetic facts, these studies cannot be directly equated to real life situations where adult bilinguals often learned arithmetic facts during childhood. So far only two fMRI studies investigated brain activation patterns during arithmetic problem solving in bilinguals (Lin et al., 2011; Wang et al., 2007). Both studies