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Numbers and functional lateralization: A visual half-field and dichotic listening study in proficient bilinguals

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ABSTRACT

Potential links between language and numbers and the laterality of symbolic number representations in the brain are still debated. Furthermore, reports on bilingual individuals indicate that the language-number interrelationships might be quite complex. Therefore, we carried out a visual half-field (VHF) and dichotic listening (DL) study with action words and different forms of symbolic numbers used as stimuli to test the laterality of word and number processing in single-, dual-language and mixed -task and language- contexts. Experiment 1 (VHF) showed a significant right visual field/left hemispheric advantage in response accuracy for action word, as compared to any form of symbolic number processing. Experiment 2 (DL) revealed a substantially reversed effect – a significant right ear/left hemisphere advantage for arithmetic operations as compared to action word processing, and in response times in single- and dual-language contexts for number vs. action words. All these effects were language independent. Notably, for within-task response accuracy compared across modalities significant differences were found in all studied contexts. Thus, our results go counter to findings showing that action-relevant concepts and words, as well as number words are represented/processed primarily in the left hemisphere. Instead, we found that in the auditory context, following substantial engagement of working memory (here: by arithmetic operations), there is a subsequent functional reorganization of processing single stimuli, whether verbs or numbers. This reorganization – their weakened laterality – at least for response accuracy is not exclusive to processing of numbers, but the number of items to be processed. For response times, except for unpredictable tasks in mixed contexts, the "number problem" is more apparent. These outcomes are highly relevant to difficulties that simultaneous translators encounter when dealing with lengthy auditory material in which single items such as number words (and possibly other types of key words) need to be emphasized. Our results may also shed a new light on the "mathematical savant problem".

1. Introduction

There is compelling evidence that numbers are processed in the human parietal and ventro-lateral visual cortex (Dehaene et al., 2003, 2004; Eger et al., 2003; Fias et al., 2003; Göbel et al., 2004; Kaufmann et al., 2008; Naccache and Dehaene, 2001; Nieder, 2005; Piazza and Eger, 2016; Piazza et al., 2004; Pinel et al., 2004; but cf. Shuman and Kanwisher, 2004). In the case of non-symbolic numbers, such as numerical quantities and approximate quantities, preponderantly bilateral processing is observed whereas for symbolic numbers (e.g., precise numerical values) clear hemispheric asymmetries have been reported (Blanco-Elorrieta and Pylkkanen, 2016; Houde and Tzourio-Mazoyer, 2003; Iversen et al., 2006; Lyons et al., 2015; Nieder, 2005; for definitions of non-symbolic and symbolic numbers, see Gomez et al., 2015). For example, the transcranial magnetic stimulation (TMS) study of Andres et al. (2005) shows that coding of precise numerical values requires the integrity of the left posterior parietal cortex (PPC). Conversely, approximate comparisons can be processed by the left and/or right PPC. Thus, representations of some forms of symbolic numbers (e.g., arithmetic operations) are predominantly left lateralized (Castro et al., 2014; Funnell et al., 2007), and this observation is coherent with a concept that left PPC plays a critical role in the processing of culturally-constructed number symbols (Notebaert et al., 2010, 2011; but cf. Göbel et al., 2006).

Most of these examples and observations are also consistent with Dehaene's triple-code model (TCM) of numerical cognition (Dehaene, 1992). Indeed, TCM assumes that the non-symbolic numbers and some forms of visually presented symbolic numbers are processed bilaterally. In sharp contrast, although in TCM arithmetic operations and numbers expressed verbally are represented in the left hemisphere, nevertheless,

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they are closely associated with language processing (e.g., in the Broca's area, middle and superior temporal gyri, supramarginal, and angular gyri; Dehaene, 1992, 2011; Klein et al., 2016; see also Schmithorst and Brown, 2004; for a meta-analytic review of brain areas connected with number processing, see Arsalidou and Taylor, 2011). Furthermore, because language is one of the most widely investigated cognitive abilities in the context of lateralization (Ocklenburg et al., 2014), a lot has been said about possible relationships between representations of symbolic numbers and representations of languages (Castro et al., 2014; Nieder, 2005; Semenza et al., 2006).

Some researchers (e.g., Purpura and Reid, 2016; Zhang, 2016) assume that language merely provides the building blocks for symbolic number acquisition, others (e.g., Nieder, 2005) that symbolic numbers are represented through language, and yet others (e.g., Van Rinsveld et al., 2015) that only large symbolic number representations (larger than 4), especially arithmetic operations – at least during the acquisition of these abilities – are mediated by language skills. However, the relation between numbers and language, or even the link between laterality of representations of symbolic numbers and arithmetic operations remains unclear (Castro et al., 2014). For example, there is also evidence that representations of numbers can be right lateralized (Carreiras et al., 2015), which suggests their independence from language and supports the notion that language is not indispensable for processing of precise numerical values (Butterworth et al., 2008; Gelman and Butterworth, 2005). Importantly, many researchers (see Domahs et al., 2010) maintain that representations of numbers are closely linked to skilled manual/finger movements (praxis). This effect may, for example, result from counting out loud and using fingers in learning arithmetic in childhood (Brozzoli et al., 2008; Domahs et al., 2008; Kaufmann et al., 2008; Sato et al., 2007; Klichowski and Przybyla, 2017). Moreover, many studies (e.g., Noel, 2005; Penner-Wilger et al., 2007; Gracia-Bafalluy and Noel, 2008) show that people – mostly children – suffering from finger agnosia usually have various problems with numbers.

Interestingly, symbolic and non-symbolic numbers may have a common representation in the human brain (Bulthe et al., 2014), yet another piece of evidence for their independence from language. Therefore, greater engagement of subdivisions of the language system – for example of the left angular gyrus – during arithmetic operations does not have to be linked to performance of arithmetic calculations per se, but may show that as such arithmetic operations are simply language-mediated processes (Dehaene et al., 2003; cf. Göbel et al., 2001).

A strong relation between representations of symbolic numbers and representation of language is particularly visible in people who use two languages (Van Rinsveld et al., 2015). For example, bilinguals very often experience difficulties in arithmetic operations performed in their second language (L2). Similarly, interpreters/simultaneous translators very frequently make mistakes or stop translating for a while when what they hear – and is supposed to be interpreted – includes a number (e.g., a date). For example, a translator says "in 2020" instead of "in 2002", or upon hearing "I studied 50 people, including 36 women" – is suddenly blocked and silent for a few seconds. The cognitive mechanisms behind such a “number problem” (Agren and van de Weijer, 2013) or the “interpreter problem” have not yet been clearly explained (Prior et al., 2015).

One of the hypotheses says that while processing symbolic numbers, especially large symbolic numbers and arithmetic operations, individuals always resort to their first language (L1). This is why when they use L2, they characteristically slow down or make mistakes when a number appears, and generally they carry out arithmetic operations in the L1 context faster and more efficiently (Spelke and Tsivkin, 2001). Conversely, other hypothesis indicates that while dealing with symbolic numbers, speakers remain in the context of L1 or L2 accordingly, and the number problem results from the disparate structures of L1 and L2, or from poor competence in L2 (Macizo et al., 2010). Consequently, it remains to be seen whether or not representations of symbolic numbers are truly related to representations of languages, as well as whether, similarly to language, these representations (or mechanisms involved in operations on symbolic numbers) are left lateralized.

To shed some new light on this issue, we investigated the processing of symbolic numbers and words in people who can fluently speak two languages. To this end, similarly to Krefta et al. (2015), we used a visual half-field (VHF) paradigm whereby action words were read in different language contexts. The use of action words for studying the relationship between language and numbers is well justified (see Andres et al., 2008) because the neural representations of numbers, as well as counting actions or gestures, seem to be closely linked to representations of praxis (e.g., Dehaene et al., 1993; Marghetis and Nunez, 2013; Nieder, 2005; Riemer et al., 2016, see also Kroliczak and Frey, 2009). However, it is also of note that the role of finger praxis in number representation and the effects of praxis skills in action verb semantics are often disputed (e.g., Crollen et al., 2011; Pulvermuller, 2013; Papeo et al., 2014).

In the current study, in line with recommendations from past VHF experiments, symbolic numbers were used in the form of number words, Arabic numerals, and arithmetic operations (Castro et al., 2014; Ratinckx et al., 2001; Menon et al., 2000). According to a suggestion by Klein et al. (2010) on the urgent need to study auditory representations of symbolic numbers and the need to compare the outcomes of visual and auditory processing, in addition to Experiment 1 using VHF processing of action words, number words, Arabic numerals and arithmetic operations in single-, dual-language and mixed contexts, we also conducted Experiment 2 with a dichotic listening (DL) test which also included the processing of action words, number words and arithmetic operations in single-, dual-language and mixed contexts.

To sum up, this study utilized simple but very reliable and compatible paradigms that enabled us to determine the lateralization of stimulus processing: VHF (e.g., Hunter and Brysbaert, 2008; Van der Haegen et al., 2011; Verma and Brysbaert, 2011) and DL (e.g., Hugdahl, 2012; Hund-Georgiadis et al., 2002). We focused on analyzing the differences in the laterality of action words and symbolic numbers, taking into account possible shifts in the lateralization of their processing in single-, dual-language and mixed contexts, and in visual and auditory contexts. The results of this study should quite unequivocally inform us about the laterality of symbolic number processing, and provide us with new knowledge about the relation between representations of numbers and languages in different contexts (single language, dual language, mixed tasks and languages, visual or auditory). Based on Krefta et al. (2015), we assumed that the dual-language or/and mixed contexts will lead to some functional reorganization of both symbolic-number and word representations, which may be indicative of some potential problems with word or number translation. More importantly, we expected that a similar reorganization may also occur in the auditory contexts, although its direction was hard to predict. Regardless of the outcome, we nevertheless assumed that the effects will be more relevant to a real life simultaneous translator/interpreter problem.

2. Experiments

The order of the two experiments described here was counterbalanced across participants. Nevertheless, for simplicity we will refer to our VHF study as Experiment 1, and to the DL study as Experiment 2. Both experiments were conducted in the *Action and Cognition Laboratory* in the Institute of Psychology at Adam Mickiewicz University in Poznan, Poland. Each experiment was taken on a different day (all the subjects visited the laboratory twice). The study obtained a positive opinion from the local Ethics Committee for Research Involving Human Subjects and was carried out in accordance with the principles of the Helsinki 2013 Declaration.

Twenty-nine healthy volunteers (18 women, age: 20–45, mean = 28.2, $SD = 6.3$) took part in Experiment 1 and Experiment 2,