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Research report

The language of arithmetic across the hemispheres: An event-related potential investigation

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ABSTRACT

Arithmetic expressions, like verbal sentences, incrementally lead readers to anticipate potential appropriate completions. Existing work in the language domain has helped us understand how the two hemispheres differently participate in and contribute to the cognitive process of sentence reading, but comparatively little work has been done with mathematical equation processing. In this study, we address this gap by examining the ERP response to provided answers to simple multiplication problems, which varied both in levels of correctness (given an equation context) and in visual field of presentation (joint attention in central presentation, or biased processing to the left or right hemisphere through contralateral visual field presentation). When answers were presented to any of the visual fields (hemispheres), there was an effect of correctness prior to the traditional N400 timewindow, which we interpret as a P300 in response to a detected target item (the correct answer). In addition to this response, equation answers also elicited a late positive complex (LPC) for incorrect answers. Notably, this LPC effect was most prominent in the left visual field (right hemisphere), and it was also sensitive to the confusability of the wrong answer – incorrect answers that were closely related to the correct answer elicited a smaller LPC. This suggests a special, prolonged role for the right hemisphere during answer evaluation.

1. Introduction

The most visible characteristic of the organizational structure of the human brain is that it is made up of two cerebral hemispheres. Although their cellular and broader neurobiological makeup is very similar, cognitive functions are often lateralized to one hemisphere or the other, and this division of labor between the hemispheres seems to be an important principle of typical neural functionality. The first report of such cognitive lateralization – for language production in the left hemisphere – was integral to the foundation of neuropsychology as a field (Broca, 1865). Interest in lateralization of cognitive specialties has since expanded outside of the language domain, with research spanning broad topics such as hemispheric differences in sensitivity to different spatial frequencies (Sergent and Hellige, 1986; Christman et al., 1991), in attentional biases in global versus local features of an object (Martin, 1979), and in bottom-up versus top-down processing (Federmeier, 2007), among others. Here, our report will focus on another domain of research that has been devoting increasing attention to the processing mechanisms and abilities of each hemisphere: numerical cognition, and arithmetic processing in particular.

An interesting analogy can be formed between sentence reading (language) and arithmetic expression reading (math), which might suggest shared underlying cognitive processes. Sentences are made up of subparts (words) that are systemically combined to convey a potentially coherent message, and, similarly, arithmetic equations are made up of subparts (numbers) with combinatorial symbols (+, %, $\times$, $-$) that can be sensibly completed (e.g., $4 \times 5 = 20$) or not. At the same time, there are important differences in the neural systems that are engaged in these two processes: at a whole-brain level, whereas the processes involved in reading words and sentences are largely associated with fronto-temporal activity (Lau et al., 2008; Price, 2012), the processes involved in understanding numbers and mathematicalexpressions are more associated with fronto-parietal activity (Chochon et al., 1999). Although the specific subregions involved seem to differ across math and language, it remains unclear to what extent the two share similar patterns of

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hemispheric lateralization overall, given the complexities of the subprocesses involved and the somewhat mixed evidence in the existing literature (described below). Therefore, the aim of this study is to use a combination of techniques novel to this field to examine the lateralization of function for arithmetic and to then compare it with prior results using the same techniques to study language lateralization.

Within the domain of mathematical cognition, the dominant perspective is that lateralization of function and its relationship to language depends heavily on the numerical skill being tested (Dehaene and Cohen, 1995). If the skill is retrieval of exact facts from memory (e.g., during multiplication), then this has been linked to verbal abilities and has been more associated with language processing and the left hemisphere. However, if the numerical skill being tapped is instead more about approximation or basic number comparison (e.g., judging the size of relative quantities), then there is less association with language and, in turn, more association with bilateral function. The evidence for each of these claims follows, starting with the relationship between lateralization of language function and memorized arithmetic facts (typically multiplication), and then proceeding through the evidence that more general numerosity concepts can be independent of left-lateralized language abilities.

In the particular domain of mathematical expression processing, calculation impairments in patients with unilateral brain lesions have been relatively more associated with damage to the left hemisphere (Jackson and Warrington, 1986; Rosselli and Ardila, 1989; Ashcraft et al., 1992). Furthermore, in patients with severed corpus callosums (i.e., "split-brain" patients), when the right hemisphere alone is forced to perform arithmetic, severe impairments are reported, particularly in multiplication (Gazzaniga and Smylie, 1984; Funnell et al., 2007). In contrast, the isolated left hemisphere is typically able to perform these arithmetic tasks above chance. When patients with left hemisphere lesions were specifically examined for the extent and type of impairments to their language and numerical skills, it was found that more severe language impairments were correlated with impairments in quantitative abilities – again, particularly for multiplication (Delazer et al., 1999). This evidence forms the basis for the argument that arithmetic fact retrieval is dependent on left-lateralized language processing abilities.

That language processing, and production in particular, tends to be lateralized to the left hemisphere is one of the most well-known features of brain organization (e.g., Geschwind and Levitsky, 1968). However, in some individuals, language production is instead lateralized to the right hemisphere (Binder et al., 1996; Bishop, 2013). An interesting question, then, is what happens to arithmetic skills when language is lateralized to the right hemisphere? In patients for whom the lateralization of both language and arithmetic skills was assessed, language lateralization influenced the arithmetic abilities of each hemisphere. Specifically, if language was left-lateralized, then the isolated right hemisphere was impaired at performing multiplication, whereas if language was right-lateralized or bilateral, then the isolated right hemisphere was above chance at multiplication (Delazer et al., 2005). This suggests that it is not just a coincidence that both language and arithmetic skills tend to be left-lateralized. Instead, they seem to track each other, either due to a shared reliance on a higher-level processing mechanism that itself tends to be lateralized, or because arithmetic skills actually depend on language abilities (as is suggested by the association between level of language impairment and level of arithmetic impairment).

The most extreme versions of this conclusion – that, without language, there can be no arithmetic fact knowledge, and that the contralateral hemisphere has no involvement in arithmetic processing – is unlikely and must still contend with evidence for dissociations between these abilities. For example, there is evidence from a TMS study that both hemispheres are causally involved in answer generation for multiplication problems (Andres et al., 2011). There has also been a long history of reporting case studies of patients for whom language and arithmetic abilities are dissociable. In several cases of patients with semantic dementia, which is a progressive neurodegenerative disorder featuring loss of semantic memory (especially in word comprehension), there are reports of successful retention of some (or all) arithmetic skills (Diesfeldt, 1993; Cappelletti et al., 2001, 2012; Crutch and Warrington, 2002). However, even in these reports, it is often the case that multiplication is the most impaired arithmetic ability when verbal memory is compromised. Thus, although there is some evidence implicating right hemisphere involvement in production of multiplication problem answers, there seems to be a strong relationship between left hemisphere language abilities and the production of answers to multiplication problems.

Outside of the domain of producing exact answers to arithmetic problems from verbal memory, and in the domain of symbolic and non-symbolic number comparison, the dependence on left-lateralized language abilities is much less apparent. Instead, there are reports that both hemispheres can compare symbolic numbers for their relative size (Andres et al., 2005; Colvin et al., 2005). Indeed, there is evidence directly linking developmental changes in subregions of the right hemisphere's parietal lobe with successful acquisition of symbolic and non-symbolic magnitude judgment abilities (Holloway and Ansari, 2010), and evidence from TMS demonstrating that disruption of these right hemisphere areas results in lower performance on tests of automatic magnitude judgment abilities (Cohen Kadosh et al., 2007).

Along with magnitude judgments, the right hemisphere also seems to be able to engage in generating answers to arithmetic problems through approximation or through step-by-step deliberative procedures. For example, the same left hemisphere lesion patients who can fail to report multiplication answers often retain explicit knowledge of arithmetic operations and the ability to deliberately apply this knowledge in addition and subtraction (e.g., Cohen et al., 2000). In one case study, errors in addition and subtraction were only small distances from the correct answer, suggesting that they were produced through tracking and manipulating conceptual quantities and magnitudes (Funnell et al., 2007).

In sum, it would appear that the right hemisphere's numerical ability is limited to answer approximation and magnitude judgments, leaving the performance of exact recall of mathematical arithmetic facts as the domain of the left hemisphere (Dehaene et al., 1999). However, there are still several aspects of this research field which remain relatively unexamined: (1) the specializations of the hemispheres seem to rely on skills that unfold under different timescales, but no time-sensitive neural measures are reported, and (2) the reports at the level of the hemisphere (i.e., in commissurotomized patients) rely on some kind of end-state explicit report from the participant, which renders it difficult to interpret failures to succeed because it is unclear at what level of processing the failure occurred. In general, these gaps leave it ambiguous whether, for example, the right hemisphere generates exact correct answers and then undergoes another process that renders those answers difficult to access and report, or whether the right hemisphere simply is not a reliable independent source from which to generate the exact answers to multiplication problems.

At present, since there are no studies using time-sensitive measures to understand how the processing of equations dynamically unfolds across the hemispheres, these questions remain open. Addressing this gap is critical given how quickly the answer evaluation process occurs – people are able to verify the correctness of simple arithmetic problems easily after less than a second of