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Expertise, inhibitory control and arithmetic word problems: A negative priming study in mathematics experts

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ABSTRACT

Solving arithmetic word problems such as *"Mary has 25 marbles. She has 5 more marbles than John. How many marbles does John have?"*, in which the relational term (more than) interferes with the arithmetic operation (subtraction), relies in part on the ability to inhibit an overlearned 'add if more or subtract if less' heuristic in children, adolescents and adults. Here, we used a negative priming (NP) paradigm to investigate whether experts in mathematics need to inhibit this heuristic when solving this type of arithmetic word problem. We found NP effects in experts in mathematics, but with a smaller amplitude than those in non-experts (N = 40). We replicate these results in a second experiment (N = 62) in which we matched experts and non-experts on general intelligence and inhibitory control ability. This suggests that experts also need to inhibit the 'add if more or subtract if less' heuristic to solve such problems but were more efficient at inhibiting the heuristic than non-experts.

1. Introduction

Solving arithmetic word problems is often challenging for school-aged children and even for adults (Verschaffel, 1994). Additive arithmetic word problems such as "*Mary has 25 marbles. She has 5 more marbles than John. How many marbles does John have?*" are typically considered to be the most difficult (e.g., Giroux & Ste-Marie, 2001; Lewis & Mayer, 1987; Morales, Shute, & Pellegrino, 1985; Riley & Greeno, 1988; Schumacher & Fuchs, 2012; Stern, 1993), in part because the relational term (i.e., more than) interferes with the arithmetic operation (i.e., subtraction). In the type of problem presented above (hereafter referred to as conflict arithmetic word problems), children are typically tempted to perform addition rather than subtraction, leading to reversal errors (a response of 30 instead of 20) characterized by adding the numbers instead of subtracting them or *vice versa* (Lewis & Mayer, 1987; Stern & Lehrndorfer, 1992; Stern, 1993; Verschaffel, De Corte, & Pauwels, 1992). According to some authors, failures to solve these problems in childhood are related to an executive failure to inhibit an overlearned arithmetic strategy or heuristic, namely the 'add if more or subtract if less' heuristic (Lubin, Houdé, & De Neys, 2015; Lubin, Vidal, Lanoë, Houdé, & Borst, 2013). The aim of the present study is to investigate whether adults with a high level of expertise in mathematics (experts in mathematics) need to inhibit the 'add if more subtract if less' heuristic to solve conflict arithmetic word problems as non-expert adults.

Although the "add if more or subtract if less" heuristic is misleading in conflict arithmetic word problems, it is an efficient strategy to solve arithmetic word problems such as *"Jane has 25 balls. Marc has 5 more balls than Jane. How many balls does Marc have?"* in which the relational term (i.e., more than) is consistent with the arithmetic operation (i.e., addition) (hereafter referred to as no-conflict arithmetic word problems). In this type of problem, the "add if more or subtract if less" heuristic leads to the correct answer (in our example, 30). Interestingly, this type of intuitive strategy emerges in early childhood, is reinforced by academic learning and is still used in adulthood (De Corte, Verschaffel, & Pauwels, 1990; Lubin et al., 2013; Tirosh, Tsamir, & Hershkovitz,

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2008; Vamvakoussi, Van Dooren, & Verschaffel, 2012). Note that this 'add if more or subtract if less' heuristic (Lubin et al., 2013; 2015) is a special case of the so-called keyword strategy characterized by children choosing the arithmetic operation based on a key word in the problem—e.g., more/less, win/lose, tall/small or the word "times" in multiplications (e.g., De Corte et al., 1990; Hegarty, Mayer, & Green, 1992; Stern, 1993; Verschaffel, 1994; Verschaffel et al., 1992).

The progressive ability to overcome reversal errors[1] when solving conflict additive arithmetic word problems — problems in which the relational term (more/less) interferes with the arithmetic operation (addition/subtraction) — seems to be rooted in part on the progressive ability to inhibit the "add if more or subtract if less" heuristic in not only children but also adolescents and adults. To demonstrate that solving conflict arithmetic word problems requires inhibition of the "add if more or subtract if less" heuristic, Lubin et al. (2013) designed a negative priming (NP) paradigm (Tipper, 1985). The NP paradigm rests on the basic principle that if you inhibit a given strategy on one trial, then the activation of this strategy on the next trial should be more difficult, as revealed by higher error rates or longer response times (e.g., Borst, Moutier, & Houdé, 2013). In this NP paradigm, participants were asked to solve a conflict problem in which they needed to inhibit the "add if more or subtract if less" heuristic and immediately afterwards to solve a no-conflict arithmetic word problem in which the heuristic was the most appropriate strategy. Sixth-graders, ninth-graders and even adults took more time to solve a no-conflict arithmetic word problem when they had previously solved a conflict arithmetic word problem than when they had previously solved a neutral arithmetic word problem that did not require them either to inhibit or to activate the "add if more or subtract if less" heuristic (e.g., *"Joe has 25 pens. Marc has 10 pens. Does Joe have more pens than Marc?"*). The results of this study suggest that the resolution of conflict arithmetic word problem relies in part on the ability to inhibit the "add if more or subtract if less" heuristic in not only children and adolescents but also adults.

This finding echoes those from many other studies showing that adults, as well as children and adolescents, are misled by heuristics in different situations and that overcoming errors in these situations is rooted in part in the ability to inhibit these heuristics (Borst, Ahr, Roell, & Houdé, 2015; Borst, Poirel, Pineau, Cassotti & Houdé, 2013b; Lanoë, Vidal, Lubin, Houdé, & Borst, 2016; Leroux et al., 2009; Lubin et al., 2015, 2013; Stavy & Tirosh, 2000; Stavy, Goel, Critchley, & Dolan, 2006; Vamvakoussi et al., 2012). These findings are in agreement with a number of theoretical accounts that assume inhibitory control is one of the core mechanisms of cognitive development (e.g., Babai, Eidelman, & Stavy, 2012; De Neys & Everaerts, 2008; De Neys & Van Gelder, 2008; Dempster & Brainerd, 1995; Houdé, 1997, 2000, 2007; Houdé & Borst, 2014, 2015; Reyna, Lloyd, & Brainerd, 2003; Simoneau & Markovits, 2003) and mathematical development in particular (e.g., Attridge & Inglis, 2015; Clayton & Gilmore, 2015; Gillard, Van Dooren, Schaeken, & Verschaffel, 2009; Gilmore, Keeble, Richardson, & Cragg, 2015; Gilmore et al., 2013; Lubin et al. 2013; Szücs, Devine, Soltesz, Nobes, & Gabriel, 2013; Van Hoof, Janssen, Verschaffel, & Van Dooren, 2014). According to one of these theoretical accounts (Houdé, 2000; Houdé & Borst, 2014, 2015), at each age, systematic errors occur in some situations, such as during the resolution of conflict arithmetic word problems, when one fails to inhibit the misleading heuristic (strategies that are rapid and often global or holistic are useful in many situations, but they are sometimes misleading) and activate the correct algorithm (strategies that are slow, demanding and analytical but that necessarily lead to a correct or logical solution, see Kahneman, 2011 for more on heuristics and algorithms). According to this view, the progressive ability to perform problems in which heuristics and algorithms are in conflict increases with age or instruction in part because of the progressive ability to inhibit the misleading heuristic and activate the correct algorithm.

This assumption has received some support by the results of developmental NP studies showing that the amplitude of the NP effect decreases with age in a Piagetian class-inclusion task (Borst, Poirel et al., 2013b), a perspective-taking task (Aïte et al., in press) and a written verb-inflection task (Lanoë et al., 2016). In all three studies, authors argued that the amplitude of the NP effect decreases with age because of the increasing ability to inhibit the misleading heuristic that causes errors in these situations. However, within this theoretical framework, few studies have investigated whether expertise in a given domain or situation is rooted in part in a greater ability to inhibit misleading heuristics (but see, e.g., Masson, Potvin, Riopel, & Brault-Foisy, 2014). This is an important question because previous studies have demonstrated that experts can still be biased by their heuristics (or intuition), although to a lesser degree than non-experts (e.g., Obersteiner, Van Dooren, Van Hoof, & Verschaffel, 2013).

In the present study, we focused on experts in mathematics and the resolution of conflict arithmetic word problems. We investigated (a) whether adults with a high level of expertise in mathematics also must inhibit the "add if more or subtract if less" heuristic to solve arithmetic word problems in which the relational term interferes with the arithmetic operation and (b) whether experts are more efficient in inhibiting this heuristic than non-experts. We asked a group of experts in mathematics (undergraduate students in math) and a group of non-experts in mathematics (undergraduate students in human science) to perform the arithmetic word problem NP paradigm designed by Lubin et al. (2013). In this paradigm, participants performed pairs of arithmetic word problems. In control pairs, no-conflict arithmetic word problems for which the "add if more or subtract if less" heuristic must be activated (e.g., *"Jane has 25 balls. Marc has 5 more balls than Jane. How many balls does Marc have?"*) were preceded by neutral word problems for which the activation or the inhibition of the "add if more or subtract if less" heuristic is not required (e.g., *"Joe has 25 pens. Marc has 10 pens. Does Joe have more pens than Marc?"*). In test trials, no-conflict arithmetic word problems were preceded by conflict arithmetic word problems for which the "add if more or subtract if less" heuristic must be inhibited (e.g., "*Mary has 25 marbles. She has 5 more marbles than John. How many marbles does John have?*"). We reasoned that if experts as non-experts must inhibit the "add if more or subtract if less" heuristic to solve conflict arithmetic word problems, then experts and non-experts should be slower or commit more errors to perform no-conflict arithmetic word problems when they are preceded by conflict arithmetic word problems than by neutral arithmetic word problems (i.e., reflecting typical NP effects). In addition, if expertise in solving conflict arithmetic word problems is rooted in part in an increased efficiency to inhibit the "add if more or subtract if less" heuristic, then the amplitude of the NP effects should be smaller in experts than non-experts.

2. Experiment 1

2.1. Method

2.1.1. Participants

Forty young adults participated in the study. Half of the

[1] Note that we focus here on additive word problems but reversal errors can also occur in more complex arithmetic word problems (e.g. multiplication/division).