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Unpacking symbolic number comparison and its relation with arithmetic in adults

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ABSTRACT

Symbolic number – or digit – comparison has been a central tool in the domain of numerical cognition for decades. More recently, individual differences in performance on this task have been shown to robustly relate to individual differences in more complex math processing – a result that has been replicated across many different age groups. In this study, we 'unpack' the underlying components of digit comparison (i.e. digit identification, digit to number-word matching, digit ordering and general comparison) in a sample of adults. In a first experiment, we showed that digit comparison performance was most strongly related to digit ordering ability – i.e., the ability to judge whether symbolic numbers are in numerical order. Furthermore, path analyses indicated that the relation between digit comparison and arithmetic was partly mediated by digit ordering and fully mediated when non-numerical (letter) ordering was also entered into the model. In a second experiment, we examined whether a general order working memory component could account for the relation between digit comparison and arithmetic. It could not. Instead, results were more consistent with the notion that fluent access and activation of long-term stored associations between numbers explains the relation between arithmetic and both digit comparison and digit ordering tasks.

1. Introduction

Symbolic representations of numbers are often investigated using a digit comparison task, both in children (e.g., Holloway & Ansari, 2009; Mussolin, Meijas, & Noël, 2010; Sasanguie, Göbel, Moll, Smets, & Reynvoet, 2013) and in adults (e.g., Castronovo & Göbel, 2012; Moyer & Landauer, 1967). In this task, participants need to indicate the larger of two presented digits. However, just what this task measures – and hence, indirectly, what underlying processes it indexes – remains somewhat unclear.

When comparing two digits (e.g., 8 and 9), several cognitive skills are required (see also Purpura & Ganley, 2014). First, one has to identify the symbol that one is presented with as an Arabic numeral (i.e., a digit). This skill has previously been investigated by symbol knowledge tasks (i.e., "Is the symbol a digit") or digit identification tasks (i.e., "Associate the digit with the magnitude it represents") and rapid automatized (digit) naming (RAN). Moreover, several studies have demonstrated that this basic skill of identifying symbols as numerals is associated with arithmetic performance (e.g. Cirino, 2011; Koponen, Salmi, Eklund & Aro, 2013; Mazzocco & Grimm, 2013; Purpura, Baroody, & Lonigan, 2013; van der Sluis, de Jong, & van der Leij, 2004; Vanbinst, Ghesquière, & De Smedt, 2012, 2015).

Second, these culturally acquired symbols need to be matched with their phonological counterpart. In cultural letter acquisition and reading, for example, an efficient mapping process between phonological and orthographic elements is crucial (Blomert & Willems, 2010). Similarly (but see McCloskey & Schubert, 2014), at some point in development – though still no consensus exists about when and in which order exactly – digits are mapped to their corresponding verbal number words (e.g. know that '/two/' is equal to '2') (Benoit, Lehalle, Molina, Tijus, Jouen, 2013; Purpura & Ganley, 2014). Recently, researchers have shown that this audiovisual mapping skill was related to arithmetic achievement

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in both adults (Sasanguie & Reynvoet, 2014) and elementary school children (Lyons, Price, Vaessen, Blomert, & Ansari, 2014).

Third, knowledge about the ordinal relations among or sequence of Arabic numerals is necessary to perform digit comparison (Turconi, Campbell, & Seron, 2006). To decide whether 9 is larger than 8, one requires ordinal information about the digits that goes beyond the simple count list. Here again, researchers recently demonstrated the presence of a relation between numerical order processing and arithmetic (Attout & Majerus, 2015; Lyons & Ansari, 2015; Lyons & Beilock, 2011; Lyons et al., 2014).

Finally, after comparing two digits, a decision must be made about which of the two digits is numerically larger/smaller. This decision process may be numerically specific (pertaining specifically to numerical stimuli), it may be more general (i.e., common to other non-numerical comparisons – e.g., which letter is closer to Z), or some combination thereof (e.g., Holloway & Ansari, 2008).

Furthermore, during the past decade, numerous researchers have demonstrated that performance on digit comparison tasks is concurrently as well as predictively associated with arithmetic. This relation is very robust and has been observed in typically developing children (e.g., Bugden & Ansari, 2011; De Smedt, Verschaffel, & Ghesquière, 2009; Holloway & Ansari, 2009; Kolkman, Kroesbergen, & Leseman, 2013; Lyons et al., 2014; Sasanguie, De Smedt, Defever, & Reynvoet, 2012; Sasanguie et al., 2013; Vanbinst et al., 2015; Vogel, Remark, & Ansari, 2015; for a meta-analysis, see Schneider et al., 2016) and in children with mathematical learning difficulties (Brankaer, Ghesquière, & De Smedt, 2014; De Smedt & Gilmore, 2011; Landerl, Fussenegger, Moll, & Willburger, 2009; Rousselle & Noël, 2007; Vanbinst, Ghesquière, & De Smedt, 2014; for a meta-analysis, see Schwenk et al., 2017). Though this relation appears to be similar in adults as well, it is worth noting that studies on this topic with adults are surprisingly few (Castronovo & Göbel, 2012; Lyons & Beilock, 2011). When performance was measured by means of reaction times (RT), this relation was the most consistent, although performance measures such as accuracy and distance effects (i.e. faster and more accurate responses to digits that are numerically further away; Moyer & Landauer, 1967) have revealed similar results (for a review, see De Smedt, Noël, Gilmore, & Ansari, 2013). In sum, individuals who are better at indicating which of two presented Arabic numerals is numerically larger tend to have better arithmetic scores. Here we examined whether the process or processes that contributed most to explaining digit comparison could also explain some or all of the widely reported relation between digit comparison and arithmetic performance.

In a first experiment, in addition to digit comparison performance itself, we also assessed each of the four candidate processes discussed above (i.e., digit identification, digit to number-word audiovisual matching, digit order judgment and letter comparison). First, we assessed which of these processes captured unique variance in the digit comparison task. Of those that did, we next asked whether they could account for some or all of the relation between digit comparison and arithmetic abilities.

2. Experiment 1

2.1. Method

2.1.1. Participants

Sixty-seven university students participated for monetary compensation. Seven participants were removed from the analyses because of missing data or because they performed too slowly or made too many errors (>3*SD* above the group mean) in one of the experimental tasks. Consequently, the final sample comprised 60 adults (M_{age} = 20.43 years; *SD* = 2.73; 50 females).

2.1.2. Procedure

Participants were tested in groups of about 20, accompanied by two experimenters. First, all participants performed a paper-and-pencil arithmetic test, which was administered in group (i.e. the instructions were read aloud for the whole group and then the participants were requested to fill in their own page). Next, the subjects performed the experimental computer tasks measuring the candidate cognitive processes discussed above: (1) fast identification, (2) audiovisual matching, (3) order judgment and (4) comparison. For this, participants sat together in the same room, but could work individually on their own computer screen, at their own pace. Each of these tasks was presented in a numerical and a non-numerical condition, leading to eight tasks which were conducted in a randomized order using a Latin square design. Afterwards, participants individually performed two reading tests.

All experimental tasks (see Fig. 1) were conducted using a 15-inch color screen connected to a computer running the Windows 7 operating system. Stimulus presentation and recording of the behavioral data (reaction times and error rates) were controlled by E-prime Professional software, version 2.0 (Psychological Software Tools, Pittsburgh, PA, USA). In all tasks, each trial was preceded with a fixation cross of 600 ms, after which two stimuli appeared (one on the left and one on the right side of the screen) and remained on the screen for 1000 ms. Afterwards, a blank was presented until a response was detected. Participants could respond (by pressing 'a' for indicating the left or 'p' for indicating the right stimulus on an AZERTY keyboard) during the stimulus presentation or during the blank. The visual stimuli were presented in white against a black background (courier new font, 40pt, Bold). The same accounted for the audiovisual tasks, except that in these tasks, an auditory presented stimulus was presented simultaneously with the two visual stimuli. These auditory stimuli (i.e., verbal number words or letter speech sounds) were digitally recorded (sampling rate 44.1 kHz, 16-bit quantization) by a Dutch female speaker. Recordings were band-pass filtered (180–10.000 Hz), resampled at 22.05 kHz, and matched for loudness. The sounds were presented binaurally through loudspeakers at about 65 dB SPL. On all tasks, subjects were instructed to respond as quickly and as accurately as possible. The inter-trial interval was 1500 ms. Each task started with five practice trials in which feedback was provided. During the experimental trials, there was no feedback.

2.1.3. Measures

2.1.3.1. Experimental tasks.

2.1.3.1.1. Fast identification tasks. The stimulus set consisted of single digits (2–8[1]; numerical condition) or letters (I, J, N, L, N, O, P, R, T, U; letter condition) and randomly chosen symbols $, #, £, @, § and €. Participants needed to indicate which of two presented stimuli was the digit (numerical condition) or the letter (non-numerical condition), in contrast to the random symbol. The digits and the letters were equally presented on the left ($n = 7$) and on the right side of the screen ($n = 7$), resulting in 14 trials, each presented 5 times. This way, the trial list of the digit and the letter condition each consisted of 70 experimental trials.

2.1.3.1.2. Audiovisual matching tasks. An auditory stimulus was presented, i.e., a number word (e.g., [aχt] (eight)), in the numerical condition or a letter-speech sound (e.g., [i.] (i)), in the non-numerical letter condition, together with two visually presented

[1] Similar as in the first study investigating the potential role of order-related processing in number comparison (Turconi et al., 2006), we used digits 2–8 in order to create close/sequential (distance 1) pairs (2–3/3–4 and 6–7/7–8) and far (distance 3) pairs (2–5/3–6 and 4–7/5–8). To keep all tasks similar, this number range was also used in the other numerical tasks (i.e., fast digit identification and audiovisual matching).