Acta Psychologica 191 (2018) 160–170

Contents lists available at ScienceDirect

Acta Psychologica

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

Magnitude processing of written number words is influenced by task, rather than notation

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ARTICLE INFO

Classification code:
2340 cognitive processes*Keywords:*
Bilingualism
Numerical cognition
Task-dependence
Notation-independence
Magnitude processing

ABSTRACT

The extent to which task and notation influence the processing of numerical magnitude is under theoretical and empirical debate. To date, behavioural studies have yielded a mixed body of evidence. Using the case of written number words in English and Chinese, we re-examined this issue. Thirty-nine bilingual participants who showed a balanced profile of language dominance in English and Chinese completed three tasks of numerical processing (Magnitude Comparison, Numerical Matching, and Language Matching) with pure English, pure Chinese, and mixed notation number words. We conducted frequentist and Bayesian statistics on the data. Magnitude processing, as indexed by the numerical distance effect (NDE), was found to be dependent on task. Specifically, the NDE occurred in all notation conditions in the Magnitude Comparison Task and mixed notation trials in the Numerical Matching Task only. However, the data indicated that magnitude processing was independent of notation. Task and notation had an interactive influence on overall speed of processing, where participants responded to Chinese number words significantly faster than other notations for the Magnitude Comparison and Numerical Matching Tasks only. Finally, Bayesian analyses indicated that task and notation do not interact to affect magnitude processing. Specifically, the Bayes Factor and posterior model probabilities of the Bayesian ANOVA yielded strongest support for the model with three main effects (Task, Notation, Numerical Distance) and two two-way interactions (Task × Numerical Distance, Task × Notation). These findings highlight the critical role of task in numerical magnitude processing, provide support for a notation-independent account of magnitude processing, and suggest that linguistic/orthographic factors, combined with task, may interact to affect overall speed of processing.

1. Introduction

Humans are able to recognise numbers in multiple notations (e.g., four, 4, ****) and process their magnitudes (e.g., judging that 7 is larger than 2). However, the extent to which task and notation conditions influence the processing of numerical magnitude is under debate. Additionally, existing studies have not yet directly addressed whether task and notation have an interactive influence on numerical magnitude processing or not. From a cognitive perspective, addressing these questions will help determine the conditions under which magnitude processing occurs, and the extent to which magnitude processing can be considered abstract or not.

1.1. The influence of task on numerical magnitude processing

Various tasks are commonly used to investigate numerical magnitude processing. One group of tasks require participants to intentionally access and process the quantity of the numerical stimuli to successfully complete the task. These include the larger/smaller than X task (e.g., Cao, Li, & Li, 2010[1]; Cohen Kadosh, 2008; Lukas, Krinzinger, Koch, & Willmes, 2014; Pinel, Dehaene, Riviere, & Lebihan, 2001; Szűcs & Csépe, 2005), the Magnitude Comparison Task (e.g., Cohen, Warren, & Blanc-Goldhammer, 2013; Goldfarb, Henik, Rubinsten, Block-David, & Gertner, 2011), and the numerical size condition in the Numerical Stroop Task (e.g., Ganor-Stern & Tzelgov, 2008; Ganor-Stern & Tzelgov, 2011; Girelli, Lucangeli, & Butterworth, 2000; Ito & Hatta, 2003; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002; Tzelgov, Meyer, & Henik, 1992). In these tasks, participants are instructed to respond

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[1] All studies reviewed in the Introduction presented stimuli in the visual (written) modality, unless otherwise specified.

https://doi.org/10.1016/j.actpsy.2018.09.010
Received 17 June 2018; Received in revised form 25 September 2018; Accepted 26 September 2018
0001-6918/

based on numerical magnitude, such as to select one out of two numbers that is larger in quantity, or to respond to whether each stimulus number is larger or smaller than a referent number.

Other tasks do not explicitly require participants to access and process the quantity of the numerical stimuli (henceforth referred to as 'non-intentional tasks'). These include the Numerical Matching (Goldfarb et al., 2011; Sasanguie & Reynvoet, 2014; Van Opstal & Verguts, 2011; Verguts & Van Opstal, 2005) and Physical Matching tasks (Dehaene & Akhavein, 1995; Ganor-Stern & Tzelgov, 2008), and the physical size condition in the Numerical Stroop Task (Cohen Kadosh, Henik, & Rubinsten, 2008; Ganor-Stern & Tzelgov, 2008; Ganor-Stern & Tzelgov, 2011; Ito & Hatta, 2003; Rubinsten et al., 2002). In these tasks, numerical magnitude is not directly relevant. In order to follow the instructions, participants do not need to activate the numerical magnitudes associated with the numerical symbols they are asked to process. Instead, participants respond to various properties of the numbers, such as whether the numerical values or the language of the numbers are the same or different, or to select the numerical symbols or written number word that is larger in physical size.

In the tasks described above, common indicators of magnitude processing include the congruity effect in the physical size condition of Numerical Stroop Tasks (e.g., Cohen Kadosh, Henik et al., 2008; Girelli et al., 2000; Schwarz & Ischebeck, 2003) and the numerical distance effect (NDE). Our study focuses on the NDE as an indicator of magnitude processing.

The NDE refers to the well-known finding that participants are typically faster and more accurate when judging between numerosities of a large numerical distance (e.g., 2 9, Distance = 7) than numerosities of a small numerical distance (e.g., 3 4, Distance = 1). Exactly which stage of cognitive processing is the locus of the NDE remains under debate. According to the dominant view, the NDE arises from the stage of magnitude representation (e.g., Dehaene, 2003; Mazzocco, Feigenson, & Halberda, 2011) where it is thought that magnitude representations have an imprecise activation pattern, resulting in more representational overlap for numerosities of a small numerical distance than those with a large distance. Other alternative views are that the NDE arises from the stage of response selection (van Opstal, Gevers, de Moor, & Verguts, 2008; Verguts, Fias, & Stevens, 2005) or a more general mechanism that can be used to comparisons regarding time, space and quantity (Cohen Kadosh, Brodsky et al., 2008; Cohen Kadosh, Henik et al., 2008; also see Krajcsi, Lengyel, & Kojouharova, 2016).

Many studies have investigated either intentional or non-intentional tasks of magnitude processing. With respect to intentional tasks, studies have consistently reported the NDE in the larger than/smaller than X task for number words in Turkish (Lukas et al., 2014), Chinese (Cao et al., 2010), Hungarian (Szűcs & Csépe, 2005), English (Pinel et al., 2001), Hebrew (Cohen Kadosh, 2008), and for Arabic numbers (e.g., Lukas et al., 2014; Pinel et al., 2001). Studies have also reported the NDE in the Magnitude Comparison task for number words in English (Cohen et al., 2013), Chinese (Campbell, Kanz, & Xue, 1999), and for Arabic numbers (e.g., Campbell et al., 1999; Duncan & McFarland, 1980; Goldfarb et al., 2011; Moyer & Landauer, 1967). Taken together, these results indicate that participants process numerical magnitude as instructed under intentional task conditions.

The NDE is less consistently reported in non-intentional tasks of magnitude processing. For example, in the Numerical Matching Task, studies have reported the NDE for mixed notation (Dehaene & Akhavein, 1995; Ganor-Stern & Tzelgov, 2008; Van Opstal & Verguts, 2011; Verguts & Van Opstal, 2005), but not mixed modality (i.e., auditory vs written) numbers (Cohen et al., 2013; Sasanguie & Reynvoet, 2014). Using this same task, other studies have reported the NDE for written number words in English (Dehaene & Akhavein, 1995) and Indian (Ganor-Stern & Tzelgov, 2008), but not Arabic numbers (Goldfarb et al., 2011; Wong & Szücs, 2013). With respect to the Physical Matching Task, Dehaene and Akhavein (1995) reported the NDE for English number words and Arabic numbers, but not mixed English-Arabic notation, whereas Ganor-Stern and Tzelgov (2008) did not find the NDE for Indian, Arabic, or mixed Indian-Arabic notation.

Few studies have investigated both intentional and non-intentional tasks of magnitude processing. Among these studies, some suggest that numerical magnitude processing is independent of task. Using a Numerical Stroop Task, Ganor-Stern and Tzelgov (2008) reported a NDE for Indian and Arabic numbers for the numerical size condition, and a size congruity effect for the physical size condition. Pina, Castillo, Cohen Kadosh, and Fuentes (2015) reported similar findings for Arabic numbers only. Moreover, Tzelgov et al. (1992) presented participants with a referent number to memorize, and then showed them one number at a time. In the intentional task condition, participants judged whether each trial was larger or smaller than the referent number in numerical magnitude. In the non-intentional task condition, participants judged whether each trial was larger or smaller than the referent number in physical size. A NDE was obtained for the intentional task condition while a size congruity effect was obtained for the non-intentional task condition. The results of these studies suggest that numerical magnitude processing is independent of task, as the markers of magnitude processing are observed in both intentional and non-intentional task conditions.

Yet, other findings suggest that numerical magnitude processing is task-dependent. For example, Ganor-Stern and Tzelgov (2008) reported a NDE for Indian and Arabic numbers for the Numerical Matching Task, but not the Physical Matching Task. Similarly, Goldfarb et al. (2011) reported a NDE for single digit Arabic numbers in the Magnitude Comparison Task, but not the Numerical Matching Task. Goldfarb et al. (2011) further proposed that whether participants process numerical magnitude depends on task demands, specifically, whether the task entails deep processing of quantity. Taken together, these results indicate that the extent to which task influences magnitude processing remains unclear.

1.2. The influence of notation on numerical magnitude processing

Humans are generally able to recognise and process numbers belonging to a variety of notations and modalities. Examples of notations include symbolic (e.g., "5") and non-symbolic (e.g., "*****") numbers, whereas examples of modalities include auditory (e.g., "/faɪv/") and written numbers. As a case in point, written number words are diverse and include number words from alphabetic scripts (e.g., English, German, Malay), logographic scripts (e.g., Chinese, Japanese Kanji, Korean Hanja) and more. Thus, exactly which notations one is familiar with depends on one's cultural and linguistic background.

The extent to which notation influences numerical magnitude processing is under theoretical and empirical debate. Most theoretical models propose that magnitude representations are independent of notation. These include the Abstract Code Model (McCloskey, 1992), the Multiroute Model of Number Processing (Cipolotti & Butterworth, 1995), and the Triple Code Model (Dehaene & Cohen, 1995).

According to the Abstract Code Model (McCloskey, 1992; McCloskey & Macaruso, 1995), the mental systems that serve numerical cognition include the number comprehension systems for Arabic and verbal numbers, the number production systems for Arabic and verbal numbers, an abstract internal representation system, and a calculation system. The system that is responsible for semantic representation of number (i.e., magnitude) is thought to be independent of notation.

The Multiroute Model of Number Processing (Cipolotti & Butterworth, 1995) extended the Abstract Code Model by adding numerical input, output, and asemantic transcoding systems. Like the Abstract Code Model, the internal magnitude representation system is thought to be abstract, or notation-independent.

The Triple Code Model (Dehaene & Cohen, 1995; Dehaene, Piazza, Pinel, & Cohen, 2003) proposes that there are three representational codes for numerical information. The visual Arabic code represents digits. The auditory verbal code represents number words. The analog