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Time processing in children with mathematical difficulties

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A R T I C L E I N F O

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A B S T R A C T

Time processing is a fundamental ability in everyday living that improves with age. It has been suggested that time processing may be related to the representation of quantity and therefore with mathematical difficulties, but the relationship and, in particular, the implications of different time intervals are still unclear. In the present study, we investigated the relationship between mathematical abilities and the ability to reproduce time intervals of different lengths to test whether children with mathematical difficulties would also exhibit temporal impairment especially when long time intervals are involved. Twenty children with mathematical difficulties and twenty matched children without difficulties were administered a time reproduction task using short standard intervals (500 ms, 1000 ms, and 1500 ms) and long standard intervals (4 s, 9 s, and 14 s). Results showed lower temporal abilities in children with mathematical difficulties, which were particularly evident when the standard intervals were long, thus supporting the hypotheses of a relationship between mathematical and time processing abilities and of distinct systems to process time.

1. Introduction

One of the important dimensions that control our lives and a large part of our daily actions is time. Accurate time processing assists in the ability to predict, anticipate, and respond competently to everyday situations and/or future events, and is a basic aspect of our human adaptive system (Buhusi & Meck, 2005; Grondin, 2010). In particular, we all perceive and estimate time ranging from milliseconds to seconds in order to represent our external environment and a crucial use of temporal information concerns behaviour in the present time (Block, Zakay, & Hancock, 1999; Grondin, 2010; Pöppel, 1988). For example, crossing a busy street requires estimation of speed and time (Hancock & Manser, 1997; Wann, Edgar, & Blair, 1993). The control of time durations in the order of seconds may be related to the management of quantities sequentially presented. Because most our everyday situations involve temporal judgments, it is important to comprehend the development of underlying temporal processes.

In particular, a relationship between time processing and quantitative reasoning has been hypothesised. In fact, there are a variety of links between humans' estimates of time, space, and numbers, suggesting that our ability to make sense of time, space and numerosity develops from a single magnitude processing system (Bonato, Zorzi, & Umiltà, 2012; Cantlon, Platt, & Brannon, 2009; Cappelletti, Freeman, & Cipolotti, 2009). Meck and Church (1983) proposed that both time and numbers are encoded by an accumulating mechanism, and found that amphetamine administration equally affects time and number perception in rats. More recently, A Theory of Magnitude (ATOM; Walsh, 2003) assumes that "time and quantity estimation operate on similar and partly shared accumulation principles". According to ATOM, numerosity is acquired by learning associations between magnitudes of different dimensions, as "specialisations for time, space, and quantity develop from a single magnitude system operating from birth" (Walsh, 2003, p 484) presumably related to a common neural representation in the intra-parietal cortex.

Behavioural studies with healthy children and adults provide evidence for a direct link between time perception and number comprehension (Bonato et al., 2012; Hayashi, Valli, & Carlson, 2013), and between time perception and arithmetic abilities (Brown, 1997; Skagerlund & Träff, 2016). In particular, previous studies showed that numbers automatically bias attention to the left or to the right (Fischer, Castel, Dodd, & Pratt, 2003) and this might affect time perception (Alards-Tomalin, Walker, Kravetz, & Leboe-McGowan, 2016; Vicario, 2011; Vicario et al., 2008). For example, to test the number-time interaction, Vicario et al. (2008) used visual stimuli representing digits (1 and 9) presented in the centre of the screen or in the right and left space. Results showed that regardless of digit magnitude, the duration of stimuli presented in the left hemispace was underestimated and the duration of stimuli presented in the right hemispace was overestimated. Moreover, time perception was affected by the numerical magnitude of the presented stimulus, with time underestimation of stimuli of low magnitude and time overestimation of stimuli of high magnitude (Vicario et al., 2008; see also Rammsayer & Verner, 2014; Alards-

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Tomalin et al., 2016). Brannon, Suanda, and Libertus (2007) found that temporal and number discrimination abilities follow the same developmental trajectory in infants. Studies with adults showed that time processing may be affected by numerosity processing (Dormal, Andres, & Pesenti, 2008; Droit-Volet, 2003), as it happens when time has to be processed together with a quantitative task (Dormal, Seron, & Pesenti, 2006; Dormal et al., 2008; Droit-Volet, 2003; Xuan, Zhang, He, & Chen, 2007).

However, other studies showed that time, space, and numbers may be processed through independent-specific mechanisms, whereby magnitude information is processed independently for each dimension (Agrillo, Piffer, & Adriano, 2013; Agrillo, Ranpura, & Butterworth, 2010; Dehaene & Brannon, 2011). In particular, it has been shown that the psychophysical function for time differs from the numbers and length in both healthy children and adults (Droit-Volet, Clément, & Fayol, 2008) and that the approximate number system and time perception do not correlate in healthy pre-school children, suggesting that the system that codes approximate numbers is distinct from the system that codes approximate time (Odic et al., 2016).

In the context of the relationship between time and number processing, a crucial variable appears represented by the length of the duration to be processed (Buhusi & Meck, 2005; Lewis & Miall, 2003). A distinction was proposed between very short intervals (milliseconds range) and long intervals (few seconds range) only the latter potentially relying on strategies involving numerical processes (i.e. counting; Clément & Droit-Volet, 2006; Gilaie-Dotan, Rees, Butterworth, & Cappelletti, 2014; Grondin, Ouellet, & Roussel, 2004; Lewis & Miall, 2003; Hayashi et al., 2013 for a review). This may have implications for the comprehension of the characteristics of temporal distortion in children with mathematical difficulties. For example, even though counting is a simple numerical skill typically acquired during childhood, people with a developmental impairment in numerical processing often have difficulty with counting and acquire this skill at later developmental stages (Butterworth, Varma, & Laurillard, 2011; Kaufmann, 2008) and this could have an influence on relatively long durations where counting is possible.

Evidence in favour of a relationship between time processing and mathematical abilities also comes from developmental studies showing that they similarly improve with age. Pouthas (1993), for example, showed that the majority of children under 7 years of age have not learned to use the conventional units (seconds, minutes, hours) of duration accurately and that this learning takes place at different times. The acquisition, of explicit time knowledge by around age 7 (Droit-Volet, Clément, & Wearden, 2001; Espinosa-Fernandez, Miró, Cano, & Buela-Casal, 2003; Espinosa-Fernandez, de la Torre Vacas, García-Viedma, García-Guitiérrez, & Torres Colmenero, 2004; Friedman, 1990; Levin & Wilkening, 1989) is paralleled by the development of mathematical knowledge, in such a way that children may, on one side, develop awareness of the importance of time, and properly process durations, and on the other side be supported in processing quantities.

Most research on mathematical disabilities, and in particular developmental dyscalculia, has focused on the ability to process numbers and arithmetical skills (e.g., Butterworth et al., 2011). However, to date, it is still unclear whether developmental dyscalculia solely affects number quantity processing or whether it extends to other non-numerical quantity dimensions such as space or time. Investigating time processing in participants with mathematical difficulties could clarify the relationship between numbers and time.

Cappelletti, Freeman, and Butterworth (2011), Cappelletti, Freeman, and Cipolotti (2011) and Gilaie-Dotan et al. (2014) tested adults with and without mathematical disabilities on time discrimination tasks with short (360 ms and 840 ms; Cappelletti, Freeman, & Butterworth, 2011; Cappelletti, Freeman, & Cipolotti, 2011) and long (12 s and 13.2 s; Gilaie-Dotan et al., 2014) temporal intervals. Results showed intact temporal abilities (sub-seconds) in mathematical disabilities participants as long as processing numbers was not part of the experimental design, but temporal performance decreased when the temporal stimuli were preceded by numerical primes. Controls did not show any number prime effect on temporal discrimination (Cappelletti, Freeman, & Butterworth, 2011; Cappelletti, Freeman, & Cipolotti, 2011). In the case of processing supra-second temporal intervals, adults with mathematical difficulties showed a specific temporal impairment and a significant correlation with mathematical proficiency, indicating that participants with lower mathematical abilities also had lower temporal accuracy. Taken together, the results from these two studies suggested a partially shared quantity system across numerical and temporal dimensions, which support both dissociations and interactions among dimensions in individuals with mathematical disabilities.

Studies that included children also showed temporal impairment in children with mathematical difficulties, but the type of observed impairment was different between studies (Allman, Pelphrey, & Meck, 2012). In all cases, visual stimuli were employed, but the temporal tasks and the temporal ranges under investigation differed between studies. In the case of Vicario, Rappo, Pepi, Pavan, and Martino (2012) and Skagerlund and Träff (2014), children with developmental dyscalculia under-estimated and presented higher temporal variability in a comparison task concerning sub-second durations. In Hurks and Van Loosbroek's (2014) study, a temporal impairment was observed with sub-second durations in verbal estimation and time production tasks. Furthermore, in Vicario et al. (2012) and Hurks and Van Loosbroek (2014) studies, no differences between groups were observed when the time reproduction task was employed, but the studies involved a limited range of intervals and measures. In fact, the failure observed in previous studies to find a significant difference between the control group and children with mathematical difficulties in a time reproduction task could be due to the methods adopted in the studies. In particular, Vicario et al.'s (2012) study utilised some standard durations that were very short and did not reflect the time processing requests involved in everyday life time processing. Moreover, the authors calculated an average among all the short durations and another average for all the long durations, without considering the different durations separately. On the other side, the study by Hurks and Van Loosbroek's (2014) only considered the relative errors whereas absolute errors and coefficients of variations may be important and help understanding temporal processing. In fact, in the case of great variations including both under-estimations and over-estimations of time, the average relative error may underscore the presence of substantial errors in time processing (Mioni, Stablum, McClintock, & Grondin, 2014).

In sum, evidence concerning time processing in children with mathematical disabilities is still scarce and unclear, especially in the case of time short-term memory as measured by a duration reproduction task, and seems affected by the range of durations that were considered. In order to deeply explore the issue, we decided to test a group of children with mathematical difficulties using a time reproduction task with short (500, 1000 and 1500 ms) and long (4, 9 and 14 s) temporal intervals, that had already successfully used by Mioni et al. (2014) and demonstrated a good discriminatory power in neurodevelopmental disorders (Mioni, Santon, Stablum, & Cornoldi, 2017). The time reproduction task allows to investigate temporal abilities as well as cognitive and short term memory functions involved in temporal processing and seems particularly appropriate for disabled children as it is easy to administer and to explain to participants, especially if - in analogy with previous research (Carelli, Forman, & Mäntylä, 2008) - the number of trials is maintained relatively low. Children were presented with schematised smiley faces (selected in order to make the task friendly) for different durations and were required to reproduce the same durations.

We hypothesised that children with mathematical disabilities should have lower temporal abilities than typically developing children and that the difference should be clearer if different measures were collected. Moreover, we hypothesised that the temporal dysfunction in children with mathematical difficulties should be more evident with