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# Time counts: Bidirectional interaction between time and numbers in human adults

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Number is known for influencing time processing, but to what extent time influences number in human adults is unclear. We investigated possible bidirectional interactions (number on time and time on number) using a novel Stroop-like task; participants compared numbers or temporal durations in congruent (larger number presented for longer duration) or incongruent conditions (smaller number presented for longer duration). Time and number tasks were presented in different blocks (Experiment 1) or within the same block of trials with task instructions provided at the offset of the stimuli (Experiment 2). Analyses of response times (RTs) and their distribution revealed that number affected time from early RTs, and time affected number at late RTs – an asymmetry observed only when time and number tasks were presented in separate blocks. Thus, carefully chosen tasks and appropriate data analysis can reveal bidirectionality between time and number, consistent with shared magnitude or decision mechanisms.



## 1. Introduction

Animals' ability to discriminate numerosities, that is, how many items are in a set (Breukelaar & Dalrymple-Afford, 1998) and the duration of events (Roberts & Church, 1978) is the basis of a model assuming a common representational mechanism for number and time (Meck & Church, 1983). Recently, this idea of a shared mechanism was formulated as A Theory of Magnitudes (ATOM), suggesting that time, number, and space share a representational mechanism but also maintain dimension-specific processes (Bueti & Walsh, 2009; Walsh, 2003).

In humans, the shared mechanism account is supported by behavioral findings showing interactions between different magnitudes (Fabbri, Cancellieri, & Natale, 2012; Oliveri et al., 2008; Walsh, 2003; Xuan, Zhang, He, & Xhen, 2007). Here *interaction* refers to the effect of a magnitude dimension, for instance number, on another magnitude dimension, such as time, on participants' responses during a cognitive task. A common approach to test for interactions between magnitudes is the use of Stroop-like tasks (Stroop, 1935), in which the effect of a task-irrelevant stimulus (e.g., word meaning) is observed on response times (RTs) associated with a task-relevant stimulus (e.g., word color).

In the field of numerical cognition, the Stroop task has been used to show that numerical information and the physical size of numbers interact in the well-known "size congruity effect" (Henik & Tzelgov, 1982). In the size-number Stroop task, numerical values are mapped on physical sizes resulting in congruent (i.e., within a pair of digits, the larger numerical value

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is also larger in physical size, e.g., 2 6) and incongruent conditions (i.e., within a pair of digits, the larger numerical value is smaller in physical size, e.g., 2 6). In different tasks, participants report either the larger number or the larger physical size, such that when reporting number, physical size is the task-irrelevant dimension and when reporting the physical size, number is the task-irrelevant dimension. Under these conditions, RTs are typically faster for congruent than for incongruent trials, irrespective of the task (i.e., judging numerical or physical size), suggesting that physical size and numerical processing influence each other (Henik & Tzelgov, 1982).

Stroop tasks have also been used to show that number and time interact (Xuan et al., 2007), although this interaction has been found to be unidirectional. That is, number usually affects time processing, but at least in adult participants, time processing has not been found to affect number processing (for a review see Bueti & Walsh, 2009). These unidirectional interactions may be the only ones reported simply because bidirectional interactions (i.e., number on time *and* time on number) were not part of the aims of previous studies (e.g., Fabbri et al., 2012; Oliveri et al., 2008; Xuan et al., 2007). Alternatively, bidirectional interactions have not yet been revealed because of intrinsic differences between time and number. For instance, number might be processed in a more automatic fashion relative to time (Bueti & Walsh, 2009; Roitman, Brannon, Andrews, & Platt, 2007), and as such, number may produce a larger congruity effect on time than time on number, resulting in an asymmetrical pattern. This idea is supported by some studies that used non-symbolic stimuli in the context of Stroop-like tasks whereby, for example, a series of flashing dots varied in numerosity or duration (Dormal, Seron, & Pesenti, 2006), such that the two stimuli were congruent (i.e., more dots lasting longer), neutral (i.e., fixed numerosity or fixed duration) or incongruent (i.e., fewer dots lasting longer). Participants' response times revealed the classical interference effect (incongruent trial RT > congruent trial RT < neutral trial RT) in the duration task, but not in the numerosity task, which was interpreted as evidence that numerical information was more automatically processed than time information (Dormal et al., 2006). Similarly, Roitman et al. (2007) used a bisection task in which both time and number information were used to classify stimuli as few/short or many/long. Participants were first trained to classify stimuli that varied in both number and duration. In a subsequent testing phase, participants bisected stimuli either varying in duration and fixed in number, or varying in number and fixed in duration. Results showed that bisection depended more strongly on number than time, which may reflect a difference in the salience of the two dimensions.

Differences in the level of automaticity could produce an asymmetrical pattern of interactions involving time and number. For example, if number is processed in a more automatic fashion relative to time, it is possible that number will produce a larger congruity effect on time than time on number, resulting in an asymmetric pattern. Understanding whether interactions between dimensions are bidirectional or not is important for understanding the processing of magnitudes and their inter-relations.

Taken together, these findings support the hypothesis that time and number interact. However, they are not conclusive regarding the nature of this interaction, that is, whether number and time interact bidirectionally and whether the interaction is symmetrical or not, a critical issue for understanding magnitude processing in general.

### *1.1. Methodological considerations in studying time and number*

Some methodological factors may explain the lack of bidirectional interactions between time and number reported in previous studies. For instance, some of these earlier studies that examined interactions between time and number were based on tasks where the duration of a test stimulus was compared to that of a previously presented reference stimulus (Oliveri et al., 2008; Vicario et al., 2008; Xuan et al., 2007). In order to successfully compare sequentially presented stimuli, participants must hold the reference duration in memory, and subsequently retrieve it for comparison to the test duration. Such comparison tasks might impose a memory load, which could be problematic when testing bidirectional interactions between number and time because memory load may affect time judgments (e.g., Koch, Oliveri, & Caltagirone, 2009) more than number judgments. If the congruity effect is asymmetrical (e.g., larger congruity effect for the time task than for the number task), it may be difficult to disentangle whether such asymmetry is driven by intrinsic properties of the magnitude dimension or by different levels of difficulty imposed by the task itself.

To avoid memory load, we designed a Stroop-like task in which number and time were presented simultaneously. Our task is novel because the simultaneous presentation of the stimuli guarantees a low memory load. Moreover, complementing previous studies that used only accuracy as a dependent variable, we analyzed RTs as well as the time course of these responses across congruity conditions for both temporal and numerical judgments.

Our time course analysis was based on an established binning procedure that is novel for this type of data. Binning is a commonly used method in cognitive research to map the time course of responses associated with interference conditions (see Cohen, Bayer, Jaudas, & Gollwitzer, 2007; De Jong, Liang, & Lauber, 1994; Hommel, 1996; Meiran & Kessler, 2008; Oberauer, 2005). The binning procedure entails dividing the entire RT distribution into a number of equal intervals from fastest to slowest time, and as such it is a sensitive way to capture possible asymmetries associated with processing time and number across response times. For example, if number and time differ in terms of the level of automaticity with which they are processed (e.g., number being processed in a more automatic fashion than time), there may be different time courses associated with time and number, such that number produces earlier interference on time processing, whereas time produces relatively late interference on numerical processing.