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Manual actions cover symbolic distances at different speed

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ABSTRACT

A privileged way of representing numbers in the human mind is along an oriented mental number line. Activation of this representation has been proposed to account for the impact of numbers on motor tasks, such as on grasping, pointing, and eye movements. Here we evaluated the impact of numbers on motor control, by exploiting the evidence that the speed reached by the manual connection of two points is correlated with their physical distance. We reasoned that, if irrelevant numbers induce a mis-perception of the distance between two points, this should be reflected in the movement speed. Results showed a speed difference in the manual connection of two numerically close numbers (i.e., connected slower) and two numerically distant numbers (i.e., connected faster), placed at equal physical distance. This *representational length effect* indicates not only that symbolic distance modulates speed movement as physical distance does, but suggests that the impact of numbers on action planning does not only involve action initiation but it extends to the definition of kinematic parameters. More generally, the reported findings show that the representation of numbers along a mental space affects our behaviour in the physical space.

1. Introduction

It is widely acknowledged that numbers are spatially mapped onto an analogical representation conceived as an oriented mental number line (Dehaene, 1992; de Hevia, Vallar, & Girelli, 2008). Empirical support for this representation comes from systematic effects observed in various numerical tasks (e.g., Dehaene, Bossini, & Giraux, 1993). For instance, the time required to compare two numbers decreases according to their numerical distance, i.e., *distance effect*, and to their size, i.e., *size effect*, in the same way that our sensory discrimination depends on the ratio between two stimuli (Cantlon, Platt, & Brannon, 2009; Moyer & Landauer, 1967). The ratio-dependent performance in number discrimination has been attributed to the psychophysical properties of the analogical numerical representation, instantiated by the similarity between numerical distance and physical distance (Hubbard, Piazza, Pinel, & Dehaene, 2005). The specific spatial mapping of numbers along this representational continuum appears to be partially modulated by visuo-scanning habits in the external space associated to the direction of the reading/writing system (see Rinaldi, Di Luca, Henik, & Girelli, 2014) with a left-small and right-large coding in western cultures, reduced or inverted in right-to-left readers (Göbel, Shaki, & Fischer, 2011).

In relation to the current study, activation of this representation has been said to account for the impact of numerical magnitude on motor tasks. For example, a spatial dislocation of numbers in digit handwriting, with small numbers being written more to the left compared to large numbers, has been attributed to the activation of a mental number line (Perrone, de Hevia, Bricolo, & Girelli, 2010). In line with a left-to-right mapping of increasing magnitudes, a temporal advantage in starting leftwards movements in response to small numbers and rightwards movements in response to large numbers has been repeatedly reported (Fischer, 2003; Fischer, Warlop, Hill, & Fias, 2004; Ishihara et al., 2006; Schwarz & Keus, 2004; Schwarz & Müller, 2006). For instance, in a pointing task, participants were required to move their hands from a central location either to the left or to the right target area, according to the parity of a centrally presented number (Fischer, 2003). As expected, leftwards movements were initiated faster when classifying small digits while rightwards movements were initiated faster when classifying large digits. Whereas these findings have been typically interpreted as an isomorphism between the processing of numerical and physical space, possibly relying on long-term memory associations, other studies have suggested a more dynamic and flexible representation of this mental continuum, that might take place in working memory (van Dijck & Fias, 2011; see also Rinaldi, Brugger, Bertolini, Bockisch, & Girelli, 2015).

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Further support for the influence of numbers on actions emerges as a compatibility effect between numerical magnitude and grip posture in grasping movements (Andres, Davare, Pesenti, Olivier, & Seron, 2004), in grasping estimation (Badets, Andres, Di Luca, & Pesenti, 2007) and in different types of grip (Lindemann, Abolafia, Girardi, & Bekkering, 2007; Moretto & di Pellegrino, 2008; see also van Dijck, Fias, & Andres, 2014). For example, in Andres et al.'s (2004) study, participants classified a number as even or odd by performing a grip closure or a grip opening. Results showed that grip closure was initiated faster in response to small numbers while grip opening was initiated faster in response to large numbers. Similarly, sensory information associated with visual size, such as auditory pitch, has been shown to shape size processing in motor planning (Rinaldi, Lega, Cattaneo, Girelli, & Bernardi, 2016).

Together, this evidence has been interpreted as reflecting the influence that numerical information exerts on action, and specifically, on movement initiation rather than on movement parameters, although so far the latter have been less systematically considered (Andres et al., 2004; Badets et al., 2007; Ishihara et al., 2006; Lindemann et al., 2007; Moretto & di Pellegrino, 2008; Schwarz & Keus, 2004; Schwarz & Müller, 2006). One exception is represented by the study of Andres and colleagues (Andres, Ostry, Nicol, & Paus, 2008; see also Namdar, Tzelgov, Algom, & Ganel, 2014), where irrelevant digits printed on visual objects influenced grip aperture only in the initial phase of movement, suggesting the impact of numbers on selection and/or action planning, rather than on action in-flight control. Moreover, using a lateralised manual pointing task, a systematic deviation of hand trajectory related to number magnitude has been reported (Song & Nakayama, 2008; see also Chapman et al., 2014). However, the still limited evidence for a magnitude effect in kinematic parameters seems, at least in part, dependent on methodology (Fischer, 2003; Vierck & Kiesel, 2010). For example, similar lateralised pointing movements were either modulated by magnitude information (Song & Nakayama, 2008) or not (Fischer, 2003) depending on the recorded variable. While movement trajectory has been proven to be sensitive to numerical information, being laterally deviated as a function of number magnitude (Song & Nakayama, 2008), movement amplitude is not influenced by numerical information (Fischer, 2003).

Overall, the extent to which numbers impact on action parameters is still a relatively unexplored and controversial phenomenon. The present study contributes to this line of research with an original and very simple task: the manual connection of two points. This paradigm has at least two main advantages: 1) it requires fast and simple goal-directed movements characterised by a relatively low individual motor variability, and 2) it allows a direct evaluation of kinematic parameters, i.e., the peak velocity.

In order to produce a correct movement, indeed, people normally estimate the physical distance between the points to be connected. For reaching and grasping movements, Fitts' Law states that movement time depends on physical distance and target size (Fitts, 1954). Critically, various kinematic properties, such as the average velocity, have been shown to correlate with the physical distance between the starting and finishing points, even in simple rapid movements (Viviani & Flash, 1995). In particular, the average velocity covaries with the linear extent of the trajectory and, similarly, changing the scale at which one traces a certain trajectory induces a comparable change in the average velocity, a phenomenon known as isochrony (Viviani & Flash, 1995).

On these grounds, we reasoned that if the numerical spatial representation holds psycho-metrical features similar to a perceptual extension (but see Doricchi, Guariglia, Gasparini, & Tomaiuolo, 2005; Longo & Lourenco, 2007), a symbolic distance, such as the one between two numbers, could impact the movement speed in the same way as physical distance does. If this is so, for a fixed physical distance, the connection of two distinct points should be modulated by the symbolic distance represented by flanker numbers. Accordingly, numerically close flankers should be connected as if they were physically closer, i.e., evoking a smaller portion of a mental number line and inducing a lower peak velocity, compared to numerically far flankers, i.e., evoking a larger portion of a mental number line and inducing higher peak velocity. Peak velocity was specifically selected as the dependent variable, because this parameter has been found to increase with physical movement amplitude (e.g., Cooke, Brown, & Cunningham, 1989).

Following this rationale, we hypothesised that the speed reached by the manual connection of two distinct points is correlated with their physical distance as well as with the symbolic distance conveyed by two delimiting flanker numbers (Experiment 1). Experiment 1 was built on a previous Baseline experiment (please see the Supplementary material) to document an orthogonal effect of numerical distance induced by task irrelevant numerical flankers. Furthermore, a control experiment with identical numbers as flankers was designed to verify whether magnitude information per se (Experiment 2) may modulate motion speed as the symbolic distance between the flankers does.

2. Experiment 1

Results from the Baseline experiment confirmed that the peak velocity reached by the manual connection of two points increases as a function of their physical distance (Fitts, 1954; Viviani & Flash, 1995; please see the Supplementary methods and the Supplementary results). On these grounds, in Experiment 1, we explored the impact of symbolic distance on motor execution by manipulating the numerical difference between two irrelevant number flankers delimiting a fixed physical distance.

2.1. Method

2.1.1. Participants

Thirty right-handed undergraduate students from the University of Milano-Bicocca (23 females; mean age 23 years, range: 19–30) underwent an individual 15 min session. All the students gave informed consent and were naive about the purpose of the experiment.

2.1.2. Procedure

The task required participants to connect two points presented on the tablet-pc screen (Hp Pavilion tx2000, tablet format: 26×16 cm, resolution: 1280×800 pixels, visual angle: $40.9° \times 28.1°$). The tablet-pc was centrally aligned with the mid-saggital plane of the participants who were required to connect, with a digitilized pen, following a left-to-right direction, two visually displayed points (diameter: 0.1 cm, 0.2°). The stimuli were presented on a green background on a tablet-pc at a distance of about 30 cm from the participant.

Notably, the points to be connected were flanked by two irrelevant Arabic numbers (see Fig. 1a). This allowed us to vary the representational numerical distance delimiting a fixed physical distance. Indeed, the numbers 1, 2, 8 and 9 were chosen to generate either numerically close pairs (distance“1”, e.g., 1–2, 8–9) or numerically far pairs (distances “6”, “7”, “8”, e.g., 2–8, 1–8, 2–9, 1–9), which were always displayed in ascending order (i.e., smaller number presented as the left flanker). Thus, pairs were balanced in terms of numbers used for both numerical distances. Each level of distance (close and far) was presented 20 times for each physical distance (6, 12 and 18 cm) for a total of 120 experimental trials. Since no effect of starting position emerged in the Baseline experiment (please see the Supplementary results), the stimuli were presented only centred on the screen. Yet, to increase stimuli variability we manipulated randomly the position of the stimulus with respect to the vertical axis (i.e., by adopting five positions). The task was preceded by ten practice trials which were not analyzed.

Subjects received visual feedback of their own graphic marks. The instructions required participants to return their hand to a central position after each trial.