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Horizontal spatial representations of time: Evidence for the STEARC effect

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ABSTRACT

It is well known that stimuli such as numerals (small *vs* large) and auditory pitches (low *vs* high) have spatial characteristics, and that responses to such stimuli are biased by the mental representation of their magnitude. Walsh (2003) has argued that any spatially and action-coded magnitude will yield a relationship between magnitude and space. Here we investigated the spatial representation of 'time' using speeded responses to the onset timing (early *vs* late) of a probe stimulus following periodic auditory clicks. Participants pressed one of the two response keys depending on whether the timing of a given probe was earlier or later than expected based on the preceding clicks. The results showed that left-side responses to early onset timing were faster than those to late onset timing, whereas right-side responses to late onsets were faster than those to early onsets when the response keys were aligned horizontally. Such a time–response congruity effect was not observed with the vertical alignment of responses. These results suggest that time is represented from left to right along the horizontal axis in space. The existence of a '*mental time line*' in space and the spatial–temporal association of response codes (STEARC) effect are discussed.

1. Introduction

Recent findings have shown that cognitive representations of stimuli such as numerals (from 1 to 9), auditory pitch (from low to high), letters of the alphabet (from A to Z), and months of the year (from January to December) have spatial characteristics, and that these characteristics influence the speed of manual responses (e.g., Fischer, 2003; Gevers et al., 2003; Rusconi et al., 2006). With respect to numerals, for example, smaller numbers (e.g., 1 and 2) facilitate left-side responses compared to right-side responses, whereas larger numbers (e.g., 8 and 9) favor right-side responses [which was called the *spatial–numerical association of response codes* (SNARC) effect] (Dehaene et al., 1993; Fischer, 2003; Fischer et al., 2003; Gevers et al., 2006; Ishihara et al., 2006; Ito and Hatta, 2004). This suggests the existence of a '*mental number line*,' i.e., a cognitive representation of the magnitude of numbers, and such a representation interacts with motor preparation in space. Similar to this space–number

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association, auditory pitch can be mediated by spatial information processing (Keller and Koch, 2006; Rusconi et al., 2006), where left-side (or lower) responses are faster than right-side (or upper) responses for lower pitches and vice versa for higher pitches [which was called the *spatial–musical association of response codes* (SMARC) effect]. In this regard, auditory pitch can be thought of in terms of magnitude information, yielding a relationship between pitch and space that is similar to the number–space association.

Studies using repetitive transcranial magnetic stimulation (rTMS) have revealed that the left inferior parietal lobule (IPL) plays an important role in number representation (Göbel et al., 2001, 2006; Sandrini et al., 2004). On the other hand, the right IPL is considered to be important for the representation of time (Basso et al., 1996; Harrington and Haaland, 1999; Rao et al., 2001). Rao et al. (2001), using event-related fMRI, demonstrated that early cortical activation in the right IPL (and also in the basal ganglia) is associated with the encoding of time intervals. Impairment of the right IPL (and/or the lateral temporal lobule) often causes unilateral neglect (Doricchi and Tomaiuolo, 2003; Driver and Mattingley, 1998; Karnath et al., 2001; Mattingley et al., 1998). Basso et al. (1996) investigated subjective stimulus duration in a patient with left visuospatial neglect. In a time interval comparison task (with visual stimuli displayed in the right hemifield), the patient overestimated stimulus durations at the neglected location; specifically, stimuli appearing on the left of the display were judged to be longer in duration than those on the right of the display. Such temporal overestimation in the neglected field was also found in an interval production task. Hillstrom et al. (2004) showed that a similar patient required more time to identify two successive visual targets when the second target appeared in the neglected left hemifield. It is evident that unilateral neglect patients with right parietal lesions show deficits in sensorimotor and cognitive spatial functions (Farne et al., 2003; Rode et al., 2003, 2001; Rossetti et al., 1998). In fact, the parietal cortex has been recognized as the heart of on-line action processing in space (Grea et al., 2002; Pisella et al., 2000; Rossetti et al., 2005). Therefore, the IPL can be considered to be responsible for processing space, time, and quantity information during sensorimotor transformations.

Recently, Walsh (2003a) argued that the IPL caters to the common need for space, time, and quantity information to be used in sensorimotor transformations, suggesting that the IPL is a generalized magnitude system for action. This is a notion that is supported by the results of studies employing patients, TMS, and fMRI (e.g., Farne et al., 2003 for spatial representation; Göbel et al., 2006 for numerical representation; Rao et al., 2001 for temporal representation). Information such as numerosity, amount, and duration may be represented symbolically (i.e., as a '*mental magnitude*') irrespective of whether information is countable or uncountable (Gallistel and Gelman, 2000; Walsh, 2003a, 2003b). Such non-verbal representations undergo a fundamental qualitative and quantitative transformation during development as soon as children learn to relate them to language (Nieder, 2005). If such mental representations of magnitude interact generally with spatial processing in action, as is observed in the SNARC and SMARC effects, it can be assumed that temporal information processing would be also mediated by spatial representations during the preparation of motor responses (Walsh, 2003a). This raises the question whether there is a space–time association that is analogous to the already established space–number association.

Walsh's framework invites the hypothesis that the cognitive representation of time (e.g., early *vs* late) may interact with spatial representations. This is the main hypothesis that is tested in the present study. If there is a congruent/incongruent association between time and space, as is the case for numerical magnitude and space, then this association should facilitate responses in the congruent situation relative to the incongruent situation. When we use music/video players in everyday life, we navigate to points at which we wish to listen/watch by pressing control buttons that are arranged according to conventions that suggest such a space–time association. These buttons are usually marked 'rewind (≪)', 'play (>)', and 'fast-forward (≫)', where each arrow presumably indicates the 'direction' in which time is perceived to flow. Thus, this may be taken to suggest the existence of a '*mental time line*' in which the representation of time is aligned spatially from left to right. Similar to what is seen in the SNARC and SMARC effects, the congruity between spatial and temporal information along the '*mental time line*' may facilitate manual responses, which may yield a *spatial–temporal association of response codes* (STEARC) effect. Based on this hypothesis, two experiments were conducted in order to clarify the role of spatial–temporal associations in the sensorimotor transformation of stimulus information into response codes. Experiment 1 tested the STEARC effect using horizontally arrayed left/right responses and Experiment 2 used vertically arrayed bottom/top responses. For the vertical dimension, we were interested in whether 'early' events would be categorized in the lower portion and 'late' in the upper portion of the vertical axis (as in the vertical SNARC and SMARC effects).

2. Experiment 1: horizontally arrayed responses

2.1. *Methods*

2.1.1. *Participants*

Twenty-seven young adults (16 males, 11 females, mean age = 24.4 years, S.D. = 3.4 years) participated in this experiment. None reported any hearing problems or physical dysfunction. All participants were native speakers of German, and none had learnt languages using right-to-left or top-to-bottom orthographies. Seventeen participants were right-handed and 10 participants were left-handed according to the Edinburgh Inventory (Oldfield, 1971). They were informed of the experimental procedures in advance and consented to take part in the experiment, which was approved by the local ethics committee. The participants remained naïve about the purpose of the experiment and the hypothesis being tested. All were paid in return for participation.

2.1.2. *Apparatus and stimuli*

Auditory click sounds were used as stimuli. A personal computer system (MEGWARE Computer, Power Line P4) with 'Presentation' software (Neurobehavioral Systems) was used to generate auditory stimuli and to record participants' responses.