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ScienceDirect
Cognition 107 (2008) 501–527
COGNITION
www.elsevier.com/locate/COGNIT

An effect of spatial–temporal association of response codes: Understanding the cognitive representations of time

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Received 15 July 2006; revised 2 October 2007; accepted 28 October 2007

Abstract

The present study addresses the question of how such an abstract concept as time is represented by our cognitive system. Specifically, the aim was to assess whether temporal information is cognitively represented through left-to-right spatial coordinates, as already shown for other ordered sequences (e.g., numbers). In Experiment 1, the task-relevant information was the temporal duration of a cross. RTs were shorter when short and long durations had to be responded to with left and right hands, respectively, than with the opposite stimulus–response mapping. The possible explanation that the foreperiod effect (i.e., shorter RTs for longer durations) is greater with right than with left hand responses is discarded by results of Experiment 2, in which right and left hand responses alternated block-wise in a variable foreperiod paradigm. Other explanations concerning manual or hemispheric asymmetries may be excluded based on the results of control experiments, which show that the compatibility effect between response side and cross duration occurs for accuracy when responses are given with crossed hands (Experiment 3), and for RTs when responses are given within one hand (Experiment 4). This pattern suggests that elapsing time, similarly to other ordered information, is represented in some circumstances through an internal spatial reference frame, in a way that may influence motor performance. Finally, in Experiment 5, the temporal duration was

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doi:10.1016/j.cognition.2007.10.011

parametrically varied using different values for each response category (i.e., 3 short and 3 long durations). The compatibility effect between hand and duration was replicated, but followed a rectangular function of the duration. The shape of this function is discussed in relation to the specific task demands.

Keyword: Foreperiod

1. Introduction

Investigation of the neural substrate of time processing has recently been the focus of an increasing number of studies (e.g., Ivry and Spencer, 2004; Lange, Kramer, & Roder, 2006; Lewis & Miall, 2006; Livesey, Wall, & Smith, 2007; Macar, Coull, & Vidal, 2006; Miniussi, Wilding, Coull, & Nobre, 1999). In spite of this growing interest in the anatomical basis of time processing, however, there is relatively little in the literature on how the cognitive system represents such an elusive concept as time.

Cognitive representation of elapsing time is likely to be at least partially visuospatial in nature. Specifically, graphic representations of time are generally consistent as far as direction is concerned: most timelines run from left to right. When time is represented in a Cartesian x-axis, for instance, shorter time values are represented on the left, whereas longer time values are shown on the right. The consistency of such a representation would fit with a cognitive origin of this convention (cf. Tversky, 1995). As another example, music is written from the leftmost to the rightmost part of the pentagram, where the notes on the left have to be executed by a musician 'before' those on the right. Moreover, Van Sommers (1984) asked participants to draw a visual representation of time. Most participants drew a horizontal timeline proceeding from left to right. In problem solving from flow charts (Krohn, 1983), participants who studied flow charts developing from left to right made fewer errors and were faster to read the flow chart and to solve the problems, than participants who used the flow charts with a right-to-left directionality. These findings are consistent with the general idea that space is often used cognitively to convey meaning (Lakoff & Johnson, 1980; Scaife & Rogers, 1996; Zacks & Tversky, 1999). Memory, reasoning, and cognitive processing in general, seem to be facilitated by visuo-spatial representations (Larkin & Simon, 1987; Scaife & Rogers, 1996; Stenning & Oberlander, 1995; Tversky, 1995).

Why should spatial representation of time develop from left to right and not, for instance, the other way round? A possible determinant of the directionality of time is constituted by the words used in a given language to describe time. English and Mandarin Chinese, for instance, speak about time horizontally and vertically, respectively. This linguistic habit seems to shape thought, as temporal judgments are faster if primed by vertical spatial arrays for Mandarin speakers and by horizontal arrays for English speakers (Boroditsky, 2001). However, in this interpretation there is the confound that not only the words used to describe time but also writing directions are different between English and Mandarin (left-to-right and top-to-down, respectively). Thus, the convention of representing time from left to right is likely to derive from the Roman writing system, which adopts a left-to-right directionality. Consistent with this hypothesis, Zwaan (1965) found that Dutch people, who read and write from left to right, associate the left side of the page with the idea of 'past'. In contrast, Israeli people, who read and write from right to left, relate this idea with the right side. Moreover, Tversky, Kugelmass, and Winter (1991) studied the way in which children from three linguistic groups, English, Arabic, and Hebrew, produced graphical representations of various relations, such as temporal, spatial, quantitative, and preference relations. An effect of directionality of the written language was present only when temporal concepts were represented: left-to-right was dominant for English speakers, right-to-left was dominant for Arabic speakers, with Hebrew speakers in the middle.

The left-to-right directionality seems to be a consistent feature of how the cognitive system represents ordered material also in other domains. As an example, the cognitive representation of numbers has been shown to be to some extent spatial in nature (Dehaene, Bossini, & Giraux, 1993). Even when number magnitude is irrelevant for the task (e.g., parity judgement), RTs tend to be shorter when relatively small numbers are responded to with a left key, and large numbers are responded to with a right key, respectively, than vice versa, at least in cultures using the Roman writing system (Dehaene et al., 1993; Zebian, 2005). This is the so-called Spatial Numerical Association of Response Codes (SNARC) effect (Dehaene et al., 1993; see also Gevers, Verguts, Reynvoet, Caessens, & Fias, 2006). According to the authors' interpretation, Arabic numerals automatically activate a magnitude code. This code is represented in terms of left and right parts of an analogical mental number line. The left and right codes generated by the representation of magnitudes cause facilitation in the case of compatible responses and interference in the case of incompatible ones (see Dehaene, 2003, for a review). On the other hand, in order to account for other related phenomena, such as the number distance and size effects, Zorzi and Butterworth (1999) developed a computational model where number magnitude is not analogically represented through a continuous mental number line but through discrete numerosity codes. These opposite views may be reconciled by assuming that multiple representations of numerical quantity exist, and that which representation is used at a given moment depends on the nature of the task (Siegler & Opfer, 2003). Furthermore, other non-numerical materials with ordinal properties, such as letters and months, have also been demonstrated to have some form of spatially coded representation as, in some conditions, they show stimulus–response (S–R) compatibility effects similar to the SNARC effect (Gevers, Reynvoet, & Fias, 2003; but see Dehaene et al., 1993, Experiment 4).

It is conceivable that analogous S–R compatibility phenomena may occur when duration is the critical stimulus feature experimentally manipulated, as duration also conveys ordered information developing from early to late. In addition, the hypothesis that the cognitive representation of time is in part spatial in nature is also suggested by anatomical evidence. Indeed, electrophysiological (Lange et al., 2006), neuropsychological (Basso, Nichelli, Frassinetti, & Di Pellegrino, 1996; Critchley, 1953; Harrington & Haaland, 1999), Transcranial Magnetic Stimulation (Bjoertomt, Cowey, & Walsh, 2002; Walsh & Pascual-Leone, 2003), and functional imaging (e.g., Rao, Mayer, & Harrington, 2001) literature shows that both spatial and temporal information may be processed within common cortical areas, such as the right inferior parietal cortex, which has been held to be the seat of a magnitude processing general system (Walsh, 2003).

The aim of the current study is to test the prediction that, if time is cognitively represented by means of spatial coordinates, in analogy to numbers and other types of ordered material, it should be possible to observe similar interfering or facilitating effects of those spatial coordinates in the performance of selected tasks. Specifically, when temporal duration has to be estimated, elapsing time may be represented progressively from left to right, at least in people using the Roman writing system. It is known that a laterally presented physical stimulus produces a shift of spatial attention to the same side of the stimulus, and this is also true for moving stimuli (e.g., Proctor, Van Zandt, Lu, & Weeks, 1993). This attentional shift, in turn, generates a spatial response code on the same direction (e.g., Umiltà & Nicoletti, 1985), which activates a congruent response and causes costs if the task-relevant response should be different from that activated, in terms of both speed and accuracy (i.e., spatial compatibility effect and Simon effect; e.g., Craft & Simon, 1970; Hommel & Prinz, 1997; Umiltà & Nicoletti, 1990).

In the light of these well-known phenomena in the spatial attention domain, and of the graphical, cognitive and anatomical links between space and time, the following prediction is made. The dynamic spatial representation of time from left to right, if it exists, may cause an analogue shift of attention and generate a spatial response code, which is accordingly updated continuously from left to right. Under this assumption, we predict that a left response will tend to be faster and/or more accurate than a right response when it is associated to a relatively short temporal duration, while a right response will tend to be faster and/or more accurate than a left one when it is associated to a relatively long duration.

2. Experiment 1

Experiment 1 was specifically designed to test whether elapsing time is mentally represented in terms of spatial coordinates developing from left to right. If this spatial representation exists, it should be possible to detect S–R compatibility effects similar to those found in other spatial compatibility tasks (see Hommel & Prinz, 1997; Umiltà & Nicoletti, 1990, for reviews).

2.1. Methods

2.1.1. Participants

Twenty healthy volunteers (11 women and 9 men) took part in Experiment 1. They were 25 years old on average (range = 18–32). All the participants were right-handed. The average score on the Edinburgh Handedness Inventory (EHI; Oldfield, 1971) was 82 (range: 55–100). All participants volunteering in the whole study were Italian speakers (mother tongue) and had a medium-high educational level (years of education $\geqslant 13$). All of them were naïve to the purpose of the experiment and were paid 6 euros per hour.

2.1.2. Apparatus and materials

Participants were tested individually in a quiet and normally illuminated room. A personal computer was used for stimulus presentation and response sampling. Visual stimuli were presented through a 19-in. VGA-display at a distance of ~60 cm. A central cross (2 yellow crossed bars, 1.0 × 0.5 cm) was used as fixation. The imperative stimulus consisted of a downward pointing white arrow (a 1.5 × 1 cm bar attached to a 0.5 cm arrowhead with a maximum width of 2 cm).

2.1.3. Procedure and task

Before beginning the experiment, each participant was required to fill in the EHI. A trial started with the central fixation cross, lasting for a foreperiod (FP) of 1 or 3 s. The two values of the FP were presented randomly on an equal number of trials. After the FP elapsed, the arrow requiring a response was presented. The task consisted of pressing ‘Z’ for a short cross duration (i.e., 1 s) and ‘/’ for a long cross duration (i.e., 3 s). The stimulus duration/response key assignment was inverted after 160 trials. The order of presentation of the two possible S–R mappings was counterbalanced across participants. After a response was detected, a 1 s blank separated one trial from the other. A familiarization block, consisting of 20 trials, preceded each experimental block with opposite S–R mappings (160 trials each). During this phase, a visual feedback was displayed for 1 s soon after the response. The feedback provided during the initial practice phases consisted of the green string (in Italian): “good! Go on with the next trial!”, for correct responses, the red string: “wrong response, be careful!” plus a sound (a 1500 Hz pure tone lasting 50 ms) for incorrect responses, and the red string: “too slow, try to be faster!” (plus the 1500 Hz sound) for slow responses (>1500 ms) or null responses. The familiarization phase was repeated until participants made two errors or less. All participants reached this criterion after 1–2 familiarization phases.

2.1.4. Data analysis

Trials were treated as errors and discarded from the RT analyses if a response was made during the FP or the first 100 ms after the arrow onset (anticipated responses), if the RT was slower than 1500 ms or no response was detected (delayed and null responses), and if the FP judgment was incorrect. A 2 × 2 repeated measures ANOVA was performed both for accuracy and mean RTs of correct trials, with FP (1 vs. 3 s) and response side (left vs. right) as the within-subjects factors. Although the FP on the preceding trial is known to interact with FP on the current trial (i.e., sequential effects; e.g., Niemi & Näätänen, 1981; Vallesi & Shallice, 2007; Vallesi, Mussoni et al., 2007), preliminary analyses did not show any significant interaction between the FP on the preceding trial and response side, which is relevant for the present purposes. For this reason, the preceding FP factor was not included in the subsequent analyses.

As the FPn × response side interaction was significant in terms of RTs (see Section 2.2), we tested whether the opposite effects of response side on the short and long FPs correlated. For this reason, the RT differences between the left and the right hand responses on the short and long FP durations were also analyzed by using a Pearson's correlation.

2.2. Results

2.2.1. Accuracy

There were virtually no anticipated responses (0.1%) and delayed or null responses (0.7%). Moreover errors in judging the cross duration were less than 4.4%. No significant effect was observed in the ANOVA concerning accuracy.

2.2.2. Reaction times

The effect of FP (i.e., cross duration) was significant [$F(1,19) = 181$, $p < .001$], indicating that RTs were shorter for the long FP than for the short one (381 vs. 507 ms). The FP × response side interaction was also significant [$F(1,19) = 6.1$, $p < .05$; see Fig. 1]. This interaction indicated that responding to the short FP was faster with the left hand than with the right one (499 vs. 516 ms), and responding to the long FP was faster with the right hand than with the left one (366 vs. 396 ms). *t*-Tests comparing left vs. right hand RTs for the short duration and for the long duration were both significant (for both, $p < .05$).

If the effects of response side on short and long FPs are due to different mechanisms, there is no reason why they should be correlated. On the other hand, if they

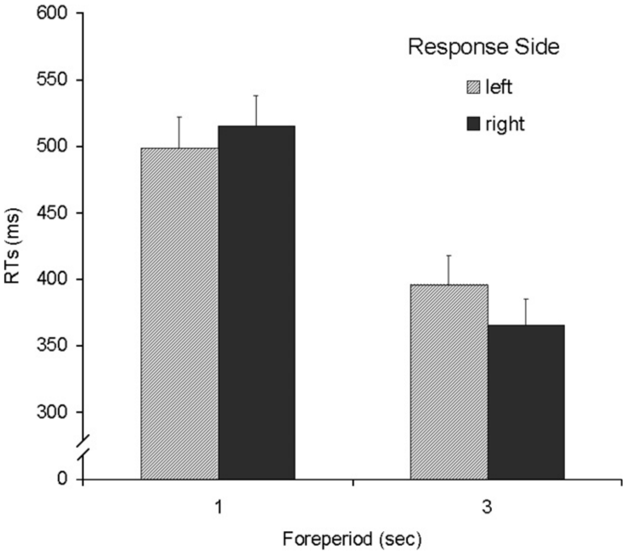

Fig. 1. Mean reaction times (and standard errors of the mean) in Experiment 1 as a function of foreperiod duration (x-axis) and responding hand (histograms).

are due to a common underlying mechanism, they should be correlated. A Pearson's correlation analysis was therefore conducted on the effect sizes (i.e., RT difference between left and right response side) in the short and long duration conditions. This analysis gave a significant positive correlation ($r = .44$, $p < .05$, see Fig. 2).

2.3. Discussion

The results of Experiment 1 confirm the literature on the FP effect, replicating this effect in a task where the FP duration is explicitly evaluated. However, the key finding is that the speed in judging the FP length (operationalized as the duration of the fixation cross) is not constant, but depends on the side of the response: responding to a short FP was faster with the left key than with the right key, whereas responding to a long FP was faster with the right key than with the left one. The opposite effects of using left and right hands on the short and long durations correlated, suggesting that they might derive from a common underlying mechanism.

As predicted in Section 1, a possible interpretation of the S–R compatibility effect found here could be that elapsing time is cognitively represented by a spatial

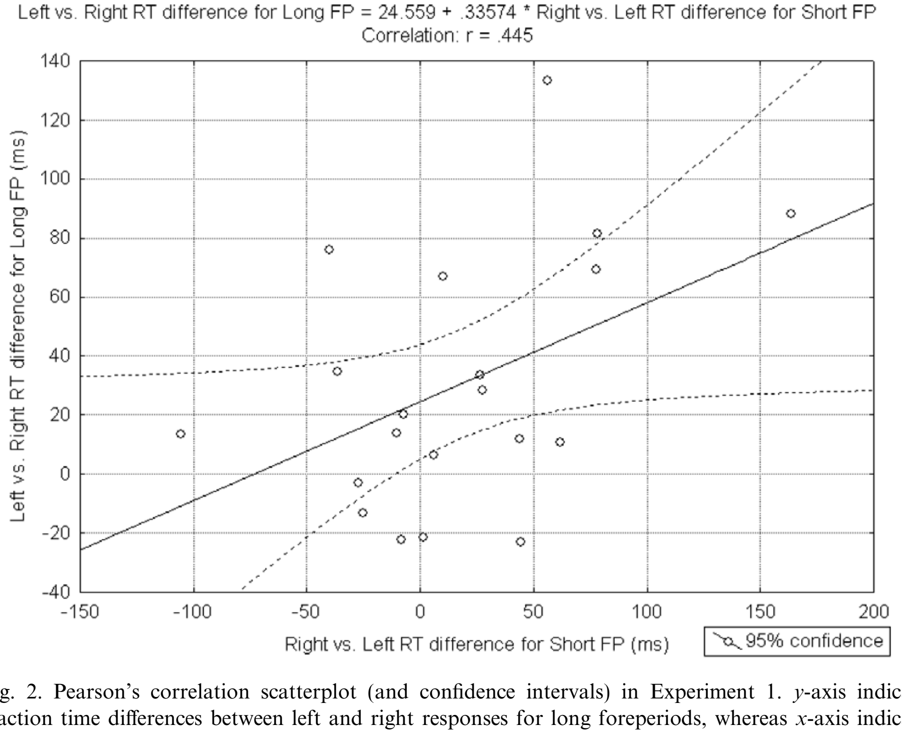

Fig. 2. Pearson's correlation scatterplot (and confidence intervals) in Experiment 1. y-axis indicates reaction time differences between left and right responses for long foreperiods, whereas x-axis indicates reaction time differences between right and left responses for short foreperiods.

vector running from left to right. Spatial attention would shift accordingly from left to right as time elapses, producing an ‘irrelevant’ response code, which develops continuously according to the spatially represented mental timeline, namely from left to right. This in turn may produce effects similar to some well-known spatial S–R compatibility effects, like the Simon effect (e.g., Hommel & Prinz, 1997). Thus, performance would be facilitated during the blocks in which the relevant response code (given by the instructions associating duration to a response) corresponds to the formally irrelevant directionality code, and delayed during the blocks in which the relevant and the irrelevant response codes go in opposite directions. In the latter case, indeed, the irrelevant response code would need to be inhibited before the ‘relevant’ correct response can be executed, increasing RTs. However, before developing this explanation further, alternative interpretations need to be carefully considered.

3. Experiment 2

In order to test the hypothesis that elapsing time is represented through spatial coordinates, a variable FP paradigm (e.g., Niemi & Näätänen, 1981) was used in Experiment 1. In this paradigm, different FPs (i.e., cross durations) alternate randomly and equiprobably across trials. As a result, RTs are shorter for longer FPs than for shorter ones. This is the so-called FP effect (Woodrow, 1914). Therefore, an alternative explanation of a compatibility phenomenon between FP duration and response side found in Experiment 1 could be the presence of a greater FP effect on either responding hand. This explanation would fit results of other compatibility effects, such as the Simon effect, which is known to be larger with the dominant hand than with the non-dominant one (e.g., Rubichi & Nicoletti, 2006). It is not possible to test this specific hypothesis directly from Experiment 1 because, in each mapping, the FP effect was given by the combination of right and left hand responses within the same block. Experiment 2 directly investigated this explanation by using a variable FP paradigm embedded in a simple RT task, where only one hand had to respond in each block.

3.1. Methods

3.1.1. Participants

Fourteen healthy participants (10 women and 4 men) volunteered in Experiment 2. They were 26 years old on average (range = 21–35). Apart from 2 left-handed participants (EHI: −55 and −80, respectively), all the others were right-handed. The average score on the EHI was 63.6 (range from −80 to 100).

3.1.2. Apparatus and materials

Apparatus and materials were basically the same as in Experiment 1. The only difference was that participants had to keep the index finger of the responding hand on the keyboard spacebar.

3.1.3. Procedure and task

A trial started with the presentation of the fixation cross, which marked the beginning of the FP (i.e., 1 vs. 3 s, 50% each, random presentation). When the FP ended, an arrow replaced the fixation. Participants were required to respond as fast as possible to the arrow by pressing the spacebar, with their right index finger in one block, and with their left index finger in the other block. The order of presentation of the 2 blocks was counterbalanced across participants. The arrow was removed by the response key-press. After a blank interval of 1 s, a new trial started. Two blocks of 80 trials (40 per each FP) were presented during each session to each participant. Ten practice trials preceded each experimental block.

3.1.4. Data analysis

Trials were treated as errors and discarded from the RT analyses if a response was made during the FP or the first 100 ms after imperative stimulus onset (anticipated responses), or if the RT was slower than 1500 ms or no response was detected (delayed and null responses). Mean RTs were submitted to a 2 FP (1 vs. 3 s) × 2 responding hand (left vs. right) repeated measures ANOVA.

3.2. Results

3.2.1. Accuracy

Anticipated and delayed responses were 1% and 0.14% of the total, respectively.

3.2.2. Reaction times

The FP effect was the only significant effect found in the ANOVA on RTs [$F(1,13) = 37.2$, $p < .001$, see Fig. 3], due to RTs being shorter for the long FP than

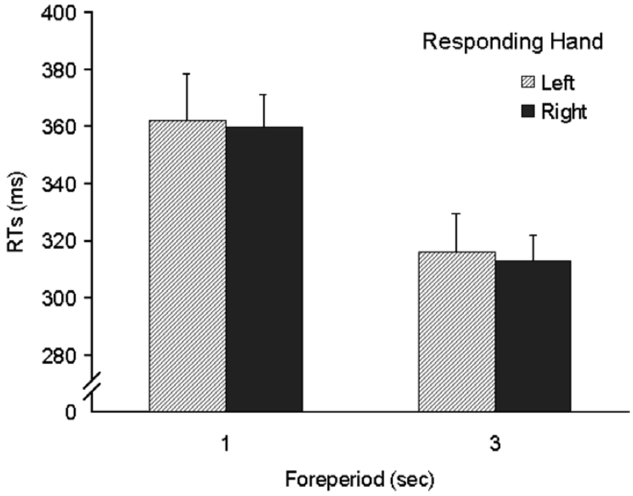

Fig. 3. Mean reaction times (and standard errors) in Experiment 2 as a function of foreperiod duration (x-axis) and responding hand (histograms).

for the short one (314 vs. 361 ms). In particular, the FP × responding hand interaction was far from significant [$F(1,13) = .2$, $p > .88$]. After the exclusion of the 2 left-handed participants, the pattern of ANOVA results was virtually identical. Moreover, the EHI score did not correlate with the RT difference between the left and right hand responses for short and long FPs [$r = -.37$, $p = .2$; $r = .49$, $p = .08$, respectively].

3.3. Discussion

Experiment 2 was designed to test whether the FP effect was greater when responding with the right hand than with the left one. No difference between hands was observed (even when the 2 left-handed participants were excluded) and the EHI score did not correlate with any between-hands RT difference in either the short or long FP condition. This pattern of results does not support the possibility that the FP by hand interaction found in Experiment 1 can be explained in terms of a greater FP effect with either hand. However, Experiment 2 did not require competition between the 2 hands, as responses had to be given with one hand at a time in 2 separate blocks of a simple RT task.

4. Experiment 3

Results of Experiment 2 excluded an account of the compatibility effect found between temporal duration and responding hand concerning a differential FP effect size in either hand. However, the possibility remains that the mechanism underlying the critical interaction in Experiment 1 derives from a within-trial competition between responding hands/hemispheres. For instance, it might be supposed that left hand/right hemisphere is better in responding to rapid temporal durations, and right hand/left hemisphere is better in responding to slower temporal durations, and that this differential ability would appear only when the selected response side switches within-blocks.

In order to choose between an explanation of the superiority of the left-short/right-long mapping in terms of the response spatial position (i.e., left vs. right response key), and another in terms of the responding hand (i.e., right vs. left hand), in Experiment 3 a manipulation was adopted, which is well-known in the spatial compatibility literature (e.g., Dehaene et al., 1993; Rubichi & Nicoletti, 2006; Wallace, 1971): participants had to respond with their hands crossed, so that the right hand should press a left key and the left hand should press a right key. In this case, the response position and the anatomical identity of the effector do not correspond.

If the interaction observed in Experiment 1 arises from asymmetric proprioceptive or motor skills between the two hands/hemispheres, we should observe an inversion of the compatibility effect with respect to the keys. If the interaction is instead due to some preferred association between the left visual hemispace with short FP and the right visual hemispace with long FPs, no change should be observed in the interaction for the response keys compared to Experiment 1.

4.1. Methods

4.1.1. Participants

Seventeen healthy volunteers (11 women and 6 men) took part in Experiment 3. A male participant was excluded because he did not follow the instructions throughout, as he used an anatomical hand position for one block (i.e., left hand on the left key and right hand on the right key). The final sample used for the analyses therefore consisted of 16 participants. They were 27 years old on average (range = 21–32). With one exception, all participants were right-handed (mean EHI score: 65; range from −75 to 100).

4.1.2. Apparatus and materials

The apparatus and materials were the same as in Experiment 1 apart from the following exception. For the responses, participants had to keep their hands crossed. The key located to the left of the body midline ('Z') was pressed by the right index finger, whereas the key located to the right ('/') was pressed by the left index finger.

4.1.3. Procedure and task

Two blocks of 160 trials each were administered. In one block, the 'Z' key had to be pressed by the right hand after a short cross duration, and the '/' key had to be pressed by the left hand after a long cross duration. The opposite S–R mapping was applied in the other block. The order of presentation of the 2 blocks was counterbalanced across participants. Half of each block was performed with the right hand standing on the top of the left one and the other half was performed with the left hand on the top of the right one. Half of the participants started each block with one position and then switched position after 80 trials. The opposite order was used for the other half of the participants. A practice phase with 20 trials (10 per each FP) was given at the beginning of each block. Similar feedback to that employed in Experiment 1 was displayed at the end of each trial during the practice phase.

4.1.4. Data analysis

The same criteria as in Experiment 1 were used to exclude incorrect trials. Accuracy and mean RTs of correct trials were analyzed by means of a 2 FPs (short vs. long) × 2 response side (left vs. right key) repeated measures ANOVA.

4.2. Results

4.2.1. Accuracy

There were virtually no anticipations during the FP. The FP × response side interaction was significant [$F(1,15) = 8.4$, $p < .01$; see Fig. 4]. Participants tended to make fewer errors when they had to respond to the short FP duration by pressing the key on the left side than by pressing the key on the right side (96.9 vs. 95.8%, respectively; *t*-test n.s.), whereas the pattern was inverted when they had to respond to the long FP duration (98.2 vs. 96.2%, with the right and left keys, respectively; *t*-test, $p < .05$).

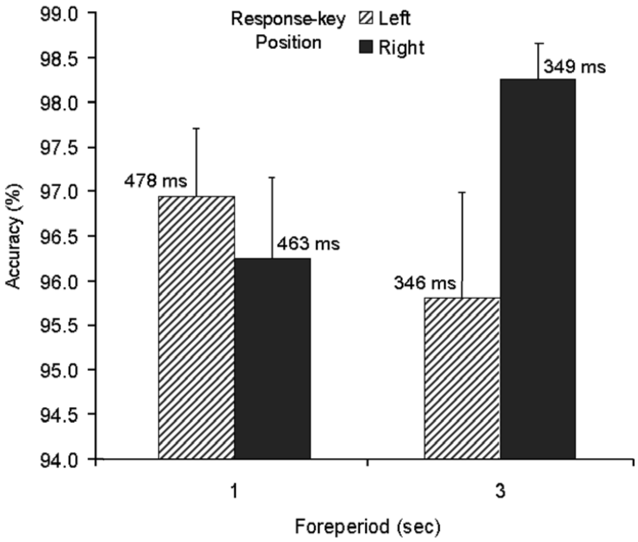

Fig. 4. Mean percentage of correct responses (bars: standard errors) and reaction times in Experiment 3 as a function of foreperiod duration (x-axis) and response-key position (histograms).

4.2.2. Reaction times

The FP effect was the only significant effect found in the ANOVA for RTs [$F(1,15) = 67.6$, $p < .001$, see Fig. 4], due to RTs being shorter for the long FP than for the short one (348 vs. 471 ms). In particular, the interaction between FP and response side was far from significant [$F(1,15) = .87$, $p = .37$].

4.3. Discussion

The only difference in the procedure with respect to Experiment 1 was that in Experiment 3 participants responded with crossed hands. Results showed a complete lack of interaction between responding hands (and response keys) and FP duration in terms of RTs, although an interaction was present in terms of accuracy. The RT null effect shows that, when hands are crossed, so that the right hand is used with the left key and the left hand with the right key, the S–R compatibility effect between response side and FP duration found in Experiment 1 totally disappears, suggesting that this effect requires hands anatomically positioned on the spatially corresponding response key in order to occur, at least in terms of speed. However, the null effect is uninformative about whether a key-related or a hand-related explanation applies to the compatibility effect found in Experiment 1. Indeed, to be compatible with the key-related account, the results should have been the same as in Experiment 1, when response keys are considered. Conversely, to be compatible with a hand-related account, the results should have been the opposite of those obtained in Experiment 1, when response keys are considered.

However, the compatibility effect was present in this experiment for accuracy, as responses to the short FP tended to be more accurate when the left key (right hand) was pressed rather than the right key (left hand), whereas responses to the long FP were significantly more accurate with a right key-press than with left one. The shift of the S–R compatibility effect from speed to accuracy could suggest a change in the participants' strategy due to an increase in task difficulty. Specifically, participants may have decided to perform the ergonomically challenging task at a relatively high speed (409 ms here vs. 443 ms in Experiment 1, where hands were anatomically positioned), despite its difficulty, with the result that they made more errors in the more difficult conditions (i.e., left and right key-presses for long and short FPs, respectively). Notably, the direction of this interaction, although only partially supported by subsequent *t*-tests, is in line with an account relating the compatibility effect to the spatial position of the response target (i.e., keys) rather than of the responding effectors (i.e., hands), in analogy with other effects, such as the spatial compatibility effect (e.g., Riggio, Gawryszewski, & Umiltà, 1986).

5. Experiment 4

Experiment 3 tested whether asymmetries between hands/hemispheres could be responsible for the compatibility effect found in Experiment 1 using crossed hands. This manipulation, however, failed to produce a clear compatibility effect between responding hands (or keys) and FP duration, at least in terms of RTs, such that it was impossible to choose between accounts related to manual/hemispheric asymmetries and accounts related to the spatial positions of the response keys. Following an analogue rationale, in Experiment 4 two fingers of the dominant hand were used for the response, in order to check if there is a temporal S–R compatibility effect between temporal duration of the stimulus and spatial position of the response even within one hand. Thus, the index and middle fingers of the dominant hand were used to give the responses. If the response key relative positions (and not hands) matter, there should be a similar compatibility effect as that found in Experiment 1 even within a single hand. In other words, if the effect found in Experiment 1 manifests itself even within one hand, any explanation concerning hemispheric asymmetries should be discarded.

5.1. Methods

5.1.1. Participants

Eighteen healthy volunteers (11 women and 7 men) took part in Experiment 4. They were 26 years old on average (range = 21–35). All participants were right-handed (EHI: 75; range: 20–100). Two additional participants were previously discarded from the analyses because they declared to have systematically counted in order to estimate the cross duration (see Section 5.1.3).

5.1.2. Apparatus and materials

The same apparatus and materials were used as in Experiment 1, apart from the fact that responses were not bimanual but should be given using the index and middle fingers of the dominant hand.

5.1.3. Procedure and task

The procedure and task were similar to those adopted in Experiment 1. The only difference was that the response should be given by pressing a key (‘B’) with the index finger of the dominant hand and another key (‘N’) with the middle finger of the same hand. The ‘B’ and ‘N’ keys were labeled and referred to in the instructions with a red and green color, respectively, in order to avoid linguistic biases. Indeed, a couple of pilot participants reported that it was difficult to associate the ‘B’ label to a long duration because ‘B’ is the initial letter of the word ‘brief’ (in Italian: ‘breve’). The red and green keys were inverted for half of the participants (i.e., ‘N’ = red; ‘B’ = green). In one block, participants had to press the key labeled with one color for a short cross duration, and the key labeled with another color for a long cross duration. In another block, the key-duration associations were inverted. The order in which the 2 key-duration mappings were administered was counterbalanced across participants. A familiarization phase (20 trials) with a feedback procedure similar to that used in Experiment 1 was adopted also here at the beginning of each block. After each familiarization phase, a test phase followed with 80 trials with a cross duration (i.e., FP) randomly varying between 1 and 3 s (50% each). Upon completion of the study, participants received a post-experimental questionnaire. In a first question, participants were asked if they had counted or used other strategies to perform the task. In a second multiple choice question, they were asked to choose a directionality for their representation of elapsing time. The available response choices were: left–right, right–left, top–down, bottom–up, clockwise, counterclock-

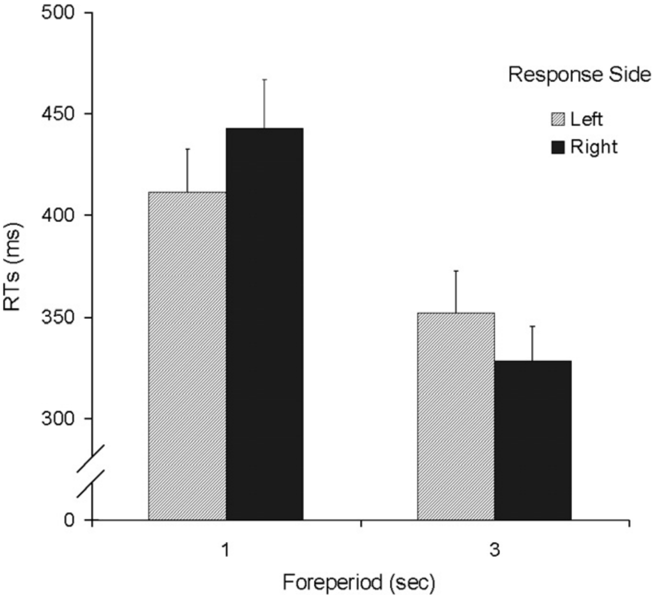

Fig. 5. Mean reaction times (and standard errors) in Experiment 4 as a function of foreperiod duration (x-axis) and response side (histograms).

wise. The order with which these alternatives appeared varied randomly across participants. The option ‘other’ was also provided.

5.1.4. Data analysis

Trials were treated as errors using the same criteria as in Experiment 1. A 2 FP duration (1 vs. 3 s) × 2 response side (left vs. right) ANOVA was employed for both accuracy and mean RTs on correct trials.

5.2. Results

5.2.1. Accuracy

Anticipated responses were 0.13%, delayed and null responses were the 0.27%, incorrect FP judgments were 5%. No effect was significant in the ANOVA concerning accuracy of the FP judgment.

5.2.2. Reaction times

The main effect of FP was significant [$F(1, 17) = 73.4$, $p < .001$], due to RTs being shorter for a long FP than for a short one (340 and 427 ms, respectively). Critically, the FP × response side interaction was also significant [$F(1, 17) = 9.3$, $p < .01$, see Fig. 6]. This interaction was due to RTs being shorter when the short FP (i.e., short cross duration) was responded to with the left key (i.e., ‘B’) rather than with the right

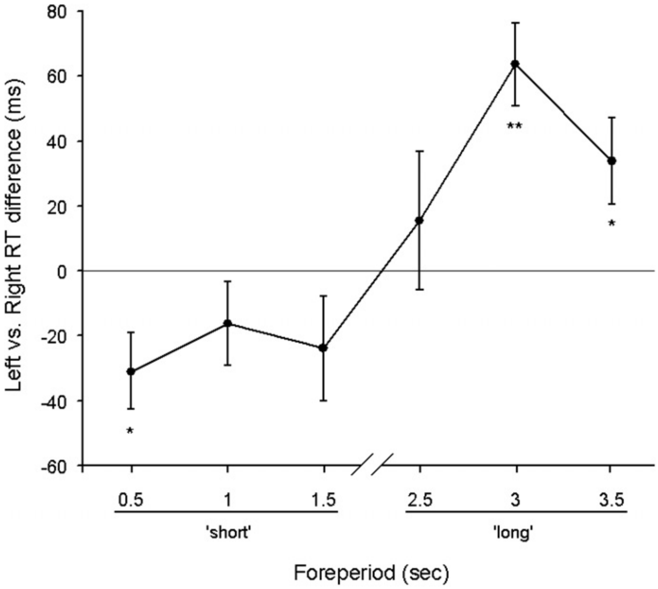

Fig. 6. Mean reaction time difference between left and right hand responses (and standard errors) in Experiment 5 as a function of foreperiod duration (x-axis). Reaction time differences between left and right hands for each foreperiod were evaluated by means of paired t-tests: $^{*}p < .05$; $^{**}p < .01$ (see the text for a more detailed statistical analysis).

key (411 vs. 443 ms, t-test, $p = .01$), and when the long FP was responded to with the right key (i.e., 'N') rather than with the left key (328 vs. 352 ms, t-test, $p < .05$) (Fig. 5).

As in Experiment 1, a further Pearson's correlation analysis was conducted between the effect size (i.e., RT difference between left and right response side) in the short and long duration conditions. This analysis showed a trend for a positive correlation ($r = .42$, $p = .078$), partially confirming results of Experiment 1.

5.2.3. Debriefings

As reported above, 2 participants out of 20 stated that they systematically used a strategy to give their response. This strategy consisted of counting how many seconds each FP lasted (sub-vocal pronunciation). More importantly, when asked to give a directionality to elapsing time by choosing one of 6 alternative answers, 18 participants chose the left-to-right option, 1 participant chose the clockwise option, and another participant chose the top-to-down option.

5.3. Discussion

The key result of Experiment 4 was the response side by FP interaction, which showed that the compatibility effect found in Experiment 1 using 2 hands can be also replicated when 2 fingers of only one hand are used for the response. Indeed, during the block in which the left key had to be pressed after a short cross duration and the right key had to be pressed after a long duration, RTs were shorter than during the block in which the key-duration mapping was reversed (i.e., left key = long duration; right key = short duration). It should be noted that response keys were never labeled as 'left' and 'right' during the instructions given to the participants, but only through labels corresponding to their color (i.e., 'red' and 'green', assignment to the left and right response keys counterbalanced across participants).

The pattern of data obtained in Experiment 4 suggests that the compatibility effect between response keys and FP durations found in Experiment 1 cannot be accounted for with explanations concerning hemispheric asymmetries, competitions between hands, or handedness (all the participants were right-handed here). During the post-test questionnaire, 18/20 participants declared they represented elapsing time from left to right. Although the possibility exists that they developed this representation because it was suggested by the modality of response (left vs. right key), this result is in line with other studies (e.g., Traugott, 1975; Zwaan, 1965, quoted by Tversky et al., 1991; Winn, 1994), where no analogous task was performed by participants before the questionnaire. Moreover, three participants spontaneously declared during the post-experimental debriefing to have had the subjective feeling that the short-left/long-right association was more natural and easier.

6. Experiment 5

The aim of Experiment 5 was to further investigate the nature of the compatibility effect found in the previous experiments by parametrically varying the FP length along a continuum, instead of using only two FP values. If a continuous spatial representation of elapsing time from left to right underlies this effect, as proposed in Section 1, a gradual influence of the FP duration should be observed on the S–R compatibility effect found in Experiment 1. This prediction is motivated by the fact that spatial attention should also progressively move from left to right along this continuous temporal line, generating a spatial response code which is continuously updated from left to right. As a consequence of this attentional orienting mechanism, the largest RT advantage should be observed with a left response to the shortest durations and with a right response to the longest durations, with these effects gradually reducing as one moves towards the center of the FP range used, where spatial attention should not be biased towards either side. A categorical function would be problematic on this account and would require consideration of alternative accounts and at least further refinements of this hypothesis.

6.1. Methods

6.1.1. Participants

Data from 27 healthy volunteers (17 women and 10 men) were included in the analyses of Experiment 5. These participants were 26 years old on average (range = 21–34). All were right-handed. The average score on the EHI was 78.2 (range: 30–100). One extra female participant was previously discarded from the analyses because she declared to have systematically counted in order to estimate the cross duration (see Section 6.1.3).

6.1.2. Apparatus and materials

Apparatus and materials were the same as in Experiment 1, apart from the following exception: the fixation cross lasted for a FP of 0.5, 1 or 1.5 s ('short' duration) and for a FP of 2.5, 3 or 3.5 s ('long' duration).

6.1.3. Procedure and task

The procedure and task were basically similar to those used in Experiment 1, with the following exceptions. The six values of the FP (i.e., cross duration) were presented randomly on an equal number of trials (30 for each). The task consisted of pressing 'Z' for a short cross duration (i.e., 0.5, 1, and 1.5 s), and '/' for a long cross duration (i.e., 2.5, 3, and 3.5 s). The stimulus duration/response key assignment was inverted after 180 trials. The order of presentation of the two possible S–R mappings was counterbalanced across participants. A familiarization block, consisting of 24 trials (4 per each cross duration), preceded each experimental block with opposite S–R mappings (180 trials each). During this practice block, similar feedback to that used in the previous experiments was provided at the end of each trial. The familiarization block was repeated until a criterion of three errors or less was reached. No more than three familiarization cycles were necessary for any participant. As for Experiment 4, after the completion of the test, participants were asked whether they had counted or used other strategies in order to perform the task.

6.1.4. Data analysis

The same criteria as in Experiment 1 were used for the analysis of the errors. A 6×2 repeated measures ANOVA was performed both for accuracy and mean RTs of correct trials, with FP (0.5, 1, 1.5, 2.5, 3, and 3.5 s) and response side (left vs. right) as the within-subject factors.

An additional analysis was carried out in order to test which of two models better accounted for the S–R compatibility effect across the different FPs. One model was that the difference between left and right RTs changes linearly with FP (0.5, 1.0, 1.5, 2.5, 3.0, and 3.5 s). Another model was that the left–right response difference changes categorically, taking on two levels, one for short FPs (0.5, 1.0, and 1.5 s) and another for long FPs (2.5, 3.0, and 3.5 s). These two models will be referred to as linear and rectangular, respectively. To compare the fit of these two models of the compatibility effect, the observed residual sums of squares were extracted for this sample under linear and rectangular models and the difference between them was calculated. Since the two models were non-nested, and there was the possibility of serial correlation among the residuals due to repeated measurement within a subject, the distribution of the difference between residual sums of squares was estimated using bootstrap samples. Bootstrap samples were constructed using an algorithm similar to that described by Wu and Zhang (2002). As a preliminary step, each subject's observed values were centered around their mean in order to reduce subsequent estimation to single parameter models. A single parameter estimate was obtained for each subject under the linear model (null hypothesis) and the subject's residual vector was obtained by fitting the rectangular model (alternative hypothesis). The next step was to construct a bootstrap sample by resampling subjects' residual vectors with replacement, resampling subjects' linear model parameter estimates with replacement, and calculating pseudo-observations based on these resampled residual vectors and parameter estimates. We decided to resample the entire residual vectors rather than individual residual values, as suggested by Wu and Zhang (2002), in order to accommodate serial correlation among residuals within a given subject. Rectangular and linear models were fit to this bootstrap sample and differences between residual sums of squares under the two models were calculated. One thousand bootstrap samples were constructed and residual sum of squares differences were calculated for each bootstrap sample.

6.2. Results

6.2.1. Accuracy

Anticipated and delayed responses were 0.53% and 1.6%, respectively. Overall errors in judging the cross duration were 10.9%. The ANOVA concerning accuracy showed only the main effect of the FP duration [$F(5,130) = 15.8$, $p < .001$]. Percentage of accurate trials was 96, 94, 84, 77, 89, 94, respectively, for the 6 FPs from 0.5 to 3.5 s. Post-hoc Tukey tests indicated that accuracy was lower on the FP of 2.5 s than on all the other FPs except for that of 1.5 s (for all the other comparisons, $p < .05$). Moreover, accuracy was lower on the FP of 1.5 s than on the FPs of 0.5 and 1 s (for both, $p < .05$). No other effect was significant.

6.2.2. Reaction times

There was a main effect of FP [$F(5,130) = 39.4$, $p < .001$]. Subsequent planned comparisons showed that RTs were different for every two adjacent FPs apart from FPs of 0.5 and 1 s (for all the other comparisons, $p < .05$). RTs were 552, 557, 602, 524, 461, and 425 ms, respectively, for each FP from 0.5 to 3.5. More relevant for the present purposes, there was a significant FP × response side interaction [$F(5,130) = 6.7$, $p < .001$], indicating that responding to short FPs was faster with the left hand than with the right one, while responding to long FPs was faster with the right hand than with the left one (see Fig. 6).

However, in order to establish whether the data better fit a linear or rectangular function, an extra analysis was carried out, as described in Section 6.1.4. Under the linear model, parameter estimates for the rate of change in RT with respect to change in FP were estimated [mean = 27.9, SD = 44.8] and a residual sum of squares (RSS) equal to 398,401 was extracted. Under the rectangular model, parameter estimates for the difference in reaction time between short and long FP were estimated [mean = 61.3, SD = 111.6] and a RSS equal to 272,640 was extracted. The observed RSS under the linear model was numerically larger than the observed RSS under the rectangular model (ΔRSS = 125,761) suggesting that the rectangular model was a better fit to our sample data. In order to evaluate whether this observed difference was extreme relative to a null sampling distribution, 1000 bootstrap samples were calculated using the random effects parameter estimates generated under the linear model (null hypothesis) and estimated background noise through residual vectors generated under the rectangular model (alternative hypothesis). If the alternative hypothesis is true, measurement error would be estimated with the residuals under the correct model. The observed RSS difference was found to be closest to the 953rd ordered difference from the bootstrap sample. This evidence points to a one-sided *p*-value of .047 for a null hypothesis significance test. Given this outcome, a rectangular function seems to account for the present data better than a linear one.

6.3. Discussion

Experiment 5 was designed to test whether the compatibility effect between responding hand and FP duration was present as a continuum when the FP length was parametrically varied along six values, or it was categorical for ‘short’ vs. ‘long’ FP ranges. The results replicated those of the previous experiments, that is relatively short and relatively long durations were responded to faster with the left and right hand, respectively. Apart from this overall compatibility effect, further analyses showed that a rectangular function fits the data better than a linear one. Therefore, the results of the present experiment seem to be at odds with the original hypothesis that elapsing time is progressively represented from left to right, and that this dynamic representation would be responsible of the S–R compatibility effect found in Experiment 1.

A possible explanation for the categorical relation between the compatibility effect and the FP duration concerns the linguistic markedness hypothesis recently proposed to explain S–R compatibility effects in other domains, such as parity effects with numbers (Nuerk, Iversen, & Willmes, 2004). In many languages, there are pairs of complementary words, one of which is marked and the other unmarked. Markedness may depend on lexical factors (Zimmer, 1964), such as the presence of prefixes (e.g., 'clear' vs. 'un-clear'), or on so-called distributive and semantic factors (e.g., 'right–left'; Lyons, 1969). According to the linguistic markedness account, performance would be facilitated when the adjectives used to label the stimulus and the response have a congruent markedness status (i.e., both are marked or unmarked), and hindered when their markedness is incongruent. On this hypothesis, 'left' and 'short' would be marked words (possibly at the semantic level), whereas 'right' and 'long' would not. That would explain why the left-short/right-long mapping is more advantageous than the opposite mapping (i.e., compatibility between the markedness status of stimulus and response categories). The reason why some words should be marked whereas others should not is however somewhat arbitrary (but see Lyons, 1969; Zimmer, 1964). Moreover, the results of Experiment 4 do not fit simply with this hypothesis. In Experiment 4 the response buttons were labeled 'green' and 'red' instead of 'left' and 'right'. However, participants still showed the S–R compatibility effect between FP and response side. On the markedness hypothesis, it is necessary to assume that the participants labeled the keys to themselves as 'left' and 'right'. Thus, the alternative possibility still exists that elapsing time is represented from left to right, even if not linearly, independently of the linguistic categories used to label stimuli and responses.[1]

Why then the S–R compatibility effect follows a rectangular function instead of a linear one could be explained by examining the task demands. The explicit request for a categorical temporal judgment might have suggested a strategy of mentally representing the temporal intervals in a dichotomous way by comparing each of them to a middle reference duration (e.g., 2 s) and to use the result of that comparison in order to split the two categories (i.e., 'short' <2 s, 'long' >2 s). This strategy might have lowered the need to access fine-grained temporal information. The adoption of a similar strategy is suggested by additional analyses. A one-way ANOVA was carried out on RT data of Experiment 5 with three levels of distance from the mid-point of 2 s (i.e., 0.5, 1, and 1.5 s for FPs of $1.5 + 2.5$, $1 + 3$, and $0.5 + 3.5$ s, respectively). This ANOVA showed a significant distance effect [$F(2,52) = 33.5$, $p < .001$], demonstrating that RTs were slowest for the middle FPs (559), conceivably because they were more difficult to distinguish from the reference mid-point, and fastest for the extreme ones (485), for which the comparison might have been easier.

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[1] This possibility is currently under further study in our laboratory. In a pilot experiment, the color of a central fixation cross changes from white to yellow during the short FP, and from yellow to red during the long FP. Participants are instructed to answer according to the final color of the cross (responding to 'yellow' with a 'left' key and to 'red' with a 'right' key). Preliminary data show that the same S–R compatibility effect as in Experiment 1 is also found in this condition. Unless one supposes the implausible scenario that participants use the (disadvantageous) strategy to re-label 'yellow' and 'red' as 'short' and 'long', or that 'yellow' and 'red' have a different markedness status, these data suggest that the effect found is independent of the linguistic labels used for the stimulus features.

An indirect task, in which temporal information is not task-relevant, would have possibly been more suitable to test the nature of the temporal representation by overcoming task-specific factors (cf. Gevers et al., 2006), provided that information about time is automatically accessed (but see Section 7). There is some evidence in support of the view that the nature of the task used may affect the shape of the compatibility effect observed. Within the different domain of numeric representation, for instance, a categorical SNARC effect has been found when number magnitude was the task-relevant information (Bachtold, Baumuller, & Brugger, 1998; Gevers et al., 2006), whereas a continuous SNARC effect was observed when it was task-irrelevant, with a parity judgment being the explicit task (Gevers et al., 2006).

Another way to address the issue would be that of parametrically varying not only the stimulus duration, but also the possible responses. A recent study adopted this approach with a temporal reproduction task (Casasanto & Boroditsky, 2008). In particular, the duration of a line (or a dot) was varied continuously and orthogonally with its left-to-right spatial displacement, and participants had to reproduce either temporal duration or spatial displacement. It was demonstrated that the irrelevant spatial displacement influenced the reproduction of temporal duration and not vice versa. Participants underestimated duration of lines that covered a shorter distance, and overestimated duration of lines that covered a longer distance, in a continuous fashion (Casasanto & Boroditsky, 2008, Fig. 1a). However, the account on which the categorical function observed here may be due to an artifact of using categorical stimuli and responses, even if suggests a possible lack of sensitivity of the tasks adopted here, could not explain the directionality of the compatibility effect found (i.e., short to long FPs being responded faster with left-to-right responses than vice versa).

7. General discussion

The present study describes an effect that can be ascribed to the S–R compatibility phenomena (e.g., Hommel & Prinz, 1997). In a series of experiments, it has been shown that, when a response is given according to the temporal duration of a stimulus (i.e., the FP), the response side affects performance. Specifically, participants are faster if they respond ‘short’ with the leftmost response and ‘long’ with the rightmost one than vice versa (e.g., Experiment 1). This pattern suggests that elapsing time is internally mapped onto spatial representations. The mechanism responsible for this phenomenon seems to be independent of asymmetries between hands in the magnitude of the variable FP effect, because when the responses are given by only one hand per block, the FP effect produced by the two hands was comparable (Experiment 2). When participants cross their hands (Experiment 3), the effect disappears in terms of speed, but manifests itself in terms of accuracy with respect to key position. In addition, any simple interpretation based on handedness or hemispheric asymmetries also has problems because the effect is also found in terms of response keys when two fingers of only one hand are used for the response (Experiment 4).

Experiment 5 tested whether the RT difference between left and right hand responses varied categorically with the FP label (‘short’ vs. ‘long’) or linearly with the FP effective duration (i.e., FPs from 0.5 to 3.5 s). The S–R compatibility effect (see Fig. 6) was better fitted by a rectangular function rather than by a linear one. This pattern may have originated by task-specific requirements. Requiring participants to dichotomously classify FPs of different length as ‘short’ vs. ‘long’ might have produced a dichotomous spatial representation of elapsing time, that is FPs might have been classified as ‘short’ and ‘long’ if they fell on the ‘left’ or on the ‘right’ of a reference mid-point of about 2 s, respectively.

The present work extends analogous findings recently obtained with temporal information conveyed by the meaning of linguistic material, such as past- and future-related words (Santiago, Lupianez, Perez, & Funes, 2007; Torralbo, Santiago, & Lupiaqez, 2006), rather than by the actual passage of time. Notably, in most experiments of these previous studies, the left–right reference frame was suggested not only by the spatial position of the response but also by that of the stimulus, which was presented either on the left or on the right side of the screen, whereas in the current study there was no spatial information conveyed by the physical attributes of the stimulus, which was always a central fixation cross. Therefore, the current findings suggest that left–right responses are a (probably) necessary and (certainly) sufficient condition for a left-to-right spatial representation of time to emerge (see also Torralbo et al., 2006, Experiment 2).

This work also extends results from previous studies where ordered sequences belonging to domains other than time, such as numbers (Dehaene et al., 1993), sound pitches (Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2006), months and letters (Gevers et al., 2003), are associated with the spatial properties of the response in a similar manner as shown here. Gevers et al. (2003) argued that the convergence of evidence from such different domains suggests that the spatial representation of ordered information is a general feature of the cognitive system, rather than being specific for the number-domain (Dehaene et al., 1993). The results reported in this paper add support to this view, extending it also to the temporal domain. However, the present study did not directly test whether temporal duration is spatially represented because of its special nature or because it is just an example of ordered information such as numbers, which the cognitive system organizes on a left-to-right mental line when particular task demands make it advantageous to do so. This issue needs to be investigated more thoroughly, for instance, by using different ordered materials (e.g., temporal and numerical) in the same task, and testing whether the compatibility effect obtained for the two domains is additive, suggesting different underlying processes, or interactive, suggesting a common mechanism (cf., Mapelli, Rusconi, & Umiltà, 2003).

With regard to the type of function followed by the between-hands RT difference along the ordered material (rectangular vs. linear), previous studies usually did not directly contrast these two kinds of functions. When evidence for linearity has been found, linear regression analyses (Fias, Lauwereyns and Lammertyn, 2001; Gevers et al., 2003; Ishihara et al., 2006) or parametric linear contrasts in ANOVA (e.g., Dehaene et al., 1993) have been used. Neither of these analyses per se can discriminate between rectangular and linear functions. Visual inspection of some figures reported in the literature on similar compatibility effects for other ordered entities (e.g., Fias et al., 2001; Gevers et al., 2003; Ishihara et al., 2006; Rusconi et al., 2006) suggests that, at least in some cases, the function fitting the results is more likely to be rectangular rather than linear, like in our Experiment 5. As already mentioned, Gevers et al. (2006), by adopting a statistical approach complementary to that used here, were able to demonstrate a rectangular function of the SNARC effect, when this was obtained during an explicit magnitude judgment. In order to account for the rectangular function, explanations related to linguistic factors (e.g., linguistic markedness) or to task demands (e.g., stimuli and responses being dichotomously defined, although stimulus duration was parametrically varied) do not seem to offer a fully satisfactory explanation of the direction of the compatibility effect obtained here (short-left/long-right). Our data can be reconciled with the hypothesis of a left-to-right representation of elapsing time, by postulating that this representation flexibly adapts its shape to the nature of the task, although this hypothesis requires future testing.

From a functional point of view, in the temporal judgment task used in experiments presented here (i.e., Experiments 1, 3, 4, and 5), it is possible to know reasonably well in advance which response should be executed at the end of the short FP as well as at the end of the long one. Although this information is available in advance, however, interference on motor performance occurs anyway, suggesting that the locus of the effect should be somehow after response selection and during response preparation. A fruitful line of investigation of the functional locus of the phenomenon may be represented by the analysis of electrophysiological components, such as the Lateralized Readiness Potential, an index of covert response selection, preparation and execution, which has been successfully used to investigate processing stages involved in other S–R compatibility effects (e.g., Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988; Keus, Jenks, & Schwarz, 2005; Vallesi, Mapelli, Schiff, Amodio, & Umiltà, 2005).

In this early stage of investigation, we will refer to the behavioral effect found here as the spatial–temporal association between response codes effect, in analogy with similar compatibility effects found in other domains, like numbers (e.g., SNARC effect; Dehaene et al., 1993) or sound pitches (SMARC effect; Rusconi et al., 2006). Notably, this effect should be distinguished from a temporal S–R compatibility phenomenon found when the duration is the feature relevant for both stimulus and response (e.g., Grosjean & Mordkoff, 2001; Kunde & Stöcker, 2002) which, contrary to the effect described here, does not imply any transfer of temporal information into the spatial domain.

It is worth noting that some differences already seem to exist from one domain to another. For instance, contrary to numbers, sound pitches, months or letters, which may show the S–R compatibility effects even when the information presented is irrelevant for the task, so far the present spatial–temporal compatibility effect has not been observed when duration is not task-relevant. An example would be that of standard variable FP paradigms with bimanual responses where no interaction between response side and FP has been observed (Vallesi, Shallice, & Walsh, 2007, Experiment 2). Even if based on a null effect, this evidence can be provisionally taken as a suggestion that, although the mental representation of time could be spatially organized, this spatial representation, unlike for other ordered materials, is not easily accessed automatically, but rather requires awareness of the passage of time, which is task-relevant when the spatial–temporal compatibility effect is observed (i.e., present Experiments 1, 4, and 5).[2]

In conclusion, our approach suggests, along with similar ones in the recent literature (e.g., Santiago et al., 2007; Torralbo et al., 2006), that it is possible to infer aspects of how the cognitive system represents an abstract concept like time, by analyzing the costs paid when the incongruence between response tendencies triggered by such a representation and task-relevant responses has to be resolved. Specifically, the present study shows a S–R compatibility effect, consisting of an improvement in performance when relatively short and long durations have to be responded to on the left and right side of space, respectively, rather than when the association between temporal duration and response side is reversed. This effect suggests that one way in which the amount of elapsed time is cognitively represented is by the use of a spatial coordinate reference frame from left to right, in a similar fashion to other ordered material such as numbers, letters, months, and pitches. This spatial representation seems to follow a categorical function, with ‘short’ and ‘long’ durations being associated to relatively faster ‘left’ and ‘right’ responses, respectively, with no difference between different durations within the ‘short’ range or within the ‘long’ one. However, whether this categorical function (as opposite to a linear one) depends on the specific task requirements of the current study or is due to more general factors cannot be disentangled at present.

Acknowledgements

This research was supported in part by a grant from PRIN to T.S. and Raffaella Rumiati by the Italian Ministry of University and Research (2005–2006). We thank three anonymous reviewers and Julia Spaniol for their valuable suggestions.

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[2] This assertion is partially weakened by preliminary results of an experiment of our laboratory, which shows that a similar effect is also observed when the task-relevant feature is not time but a color continuously changing with time. The condition in which the relevant and the irrelevant stimulus features co-vary together is however different from that of other S–R compatibility effects, such as the Simon effect and the SNARC effect, where the relevant and the irrelevant features vary orthogonally.

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