



## Research Report

# Space is a late heuristic of elapsing time: New evidence from the STEARC effect

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## ABSTRACT

To get a concrete representation of its intangible flow, culture frames elapsing time along spatially oriented mental or graphical lines, which are organised according to reading habits, from left to right in western cultures. One of the strongest evidence for this spatial representation of time is the STEARC effect (Spatial–Temporal Association of Response Codes), which consists of faster coding of “short” durations with motor responses in the left side of space and of “long” durations with responses in the right side. Here, we investigated the STEARC as a function of response speed in two different experiments in healthy participants. Surprisingly, in both sub- and supra-second ranges, we found the STEARC only when decisions on time durations were slow, while no spatial representation of time was present with fast decisions. This first demonstrates that space slowly takes over faster non-spatial processing of time flow and that it is possible to empirically separate the behavioural manifestations of the non-spatial and the nurtured spatial mechanisms of time coding.

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## 1. Introduction

To capture and communicate the flow of time, humans represent time using space (Tversky et al., 1991; Lakoff and Johnson, 1999; Boroditsky, 2000; Casasanto & Boroditsky, 2008; Bonato et al., 2012). For example, metaphors like “I left my past behind me” are derived from sensorimotor events linked to forward locomotion (Clark, 1973). Other spatial

representations of time stem from sensorimotor experiences related to cultural habits (Núñez & Sweetser, 2006; Casasanto & Bottini, 2014). In left-to-right reading cultures, the past is mentally placed to the left of the future and vice-versa in right-to-left reading cultures (Boroditsky et al., 2011; Callizo-Romero et al., 2020; Fuhrman et al., 2011; Ouellet et al., 2010; Pitt & Casasanto, 2020). This phenomenon extends to the representation of time durations. The Spatial Temporal Association of

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Response Codes effect (STEARC) shows that when visual or acoustic stimuli of various durations are presented, humans belonging to left-to-right reading cultures classify faster short durations with motor responses in the left side of space and long durations with responses in the right side (Space–Time Compatible Condition) rather than vice-versa (Space–Time Incompatible Condition; Vallesi et al., 2008, 2011; Conson et al., 2008; Ishihara et al., 2008). The STEARC is considered the most compelling evidence that the human brain represents time as intrinsically flowing along the spatial direction of reading and scanning habits and that short durations are automatically coded as if they were on the left side of space, while long durations as if they were in the right side.

Spatial compatibility effects between the side of the stimulus and that of the motor response that are found when the position of the stimulus is not relevant to the task, as for the case of duration judgments, are strongest at short RTs and decay at long RTs (De Jong et al., 1994; Rubichi et al., 1997). This has been taken as evidence that, notwithstanding its task irrelevance, the brain automatically codes stimulus position (De Jong et al., 1994; Rubichi et al., 1997). Here, by investigating the relationship between the speed of RTs and the strength of the STEARC, we wished to check whether the brain automatically and intrinsically codes the flow of time in spatial terms so that the STEARC is already found at short RTs or whether the spatial representation of time develops progressively so that the STEARC is found at long RTs though not at short ones. We anticipate that when the relationship between the strength of the STEARC and the speed of motor responses is considered, the spatial representation of time makes its appearance only at slower RTs and that, in contrast, the brain takes fast decisions on the duration of stimuli without resorting to spatial heuristics of time. These results significantly modify the assumption that time is intrinsically and automatically represented in spatial terms and show that the brain needs time to frame time in space.

## 2. Experiment 1

### 2.1. Materials and method

In a first experiment, we ran a temporal duration judgment task (Vallesi et al., 2008) to test whether elapsing time is mentally represented in spatial coordinates, i.e., the STEARC effect. Here, we analysed the time course of the Space–Time Association by dividing RTs distribution into four proportional quartiles-bins. The study was designed in accordance with the principles of the Declaration of Helsinki and was approved by the Ethical Committee of the Department of Psychology–Sapienza University of Rome (Protocol Number: 0002619).

### 2.2. Participants

To determine the number of participants, we ran an a priori power analysis (G\*Power program, Faul et al., 2007). Using the effect size  $f(U) = .568$  derived from the previous study of Vallesi et al. (2008), the analysis showed that a total of 22 participants would be needed to have a power of .95 when

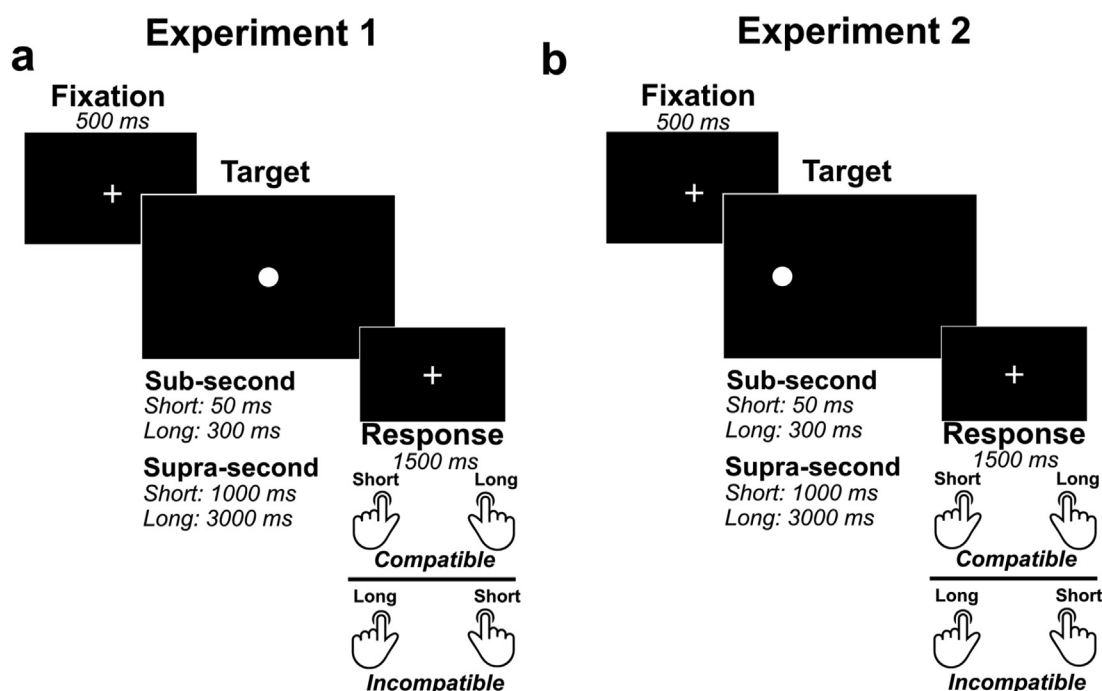
employing the traditional .05 alpha criterion of statistical significance for repeated measures within factors ANOVA. Based on this preliminary analysis, in Experiment 1, we tested an initial sample of 26 healthy adult right-handed participants (Exp 1: 17 F and 9 M; mean age: 23.4 y; data collected in 2021/2022). One participant (F) was excluded from the analyses due to excessive errors (42%).

### 2.3. Apparatus and stimuli

Experiments were administered through the open-source software OpenSesame (<https://osdoc.cogsci.nl/3.3/>; Mathôt, Schreij, & Theeuwes, 2012). Each trial started with the 500 ms presentation of a white central fixation cross ( $1.5^\circ \times 1.5^\circ$ ). At the end of this delay, a white dot target (diameter =  $2^\circ$ ) on a dark grey background was presented as a temporal duration stimulus. In Exp 1, the target replaced the central fixation cross, while in Exp 2, it was centred  $8^\circ$  to the left or the right of central fixation. Although most studies have investigated the STEARC with time durations taken from the supra-second range (for review, see von Sobbe et al., 2019), here we wish to investigate the STEARC also in the sub-second range. In the supra-second range, short-duration targets lasted 1 s and long-duration ones 3 s. In the sub-second range, short-duration targets lasted 50 ms and long duration ones 300 ms. At the end of the target period, 1500 ms were allowed for response. The inter-trial interval started after the participant's response and lasted for 500 ms. Participants were asked to judge the short/long duration of targets by pressing on the computer keyboard the left-side ("x") button with the left index finger or the right-side button ("m") with the right index finger (see Fig. 1a). In each experiment, in one block of trials short durations were associated with the left-side button and long durations with the right-side button (Compatible condition). In another block of trials, the association between response side and target duration was reversed (Incompatible condition). In each experiment, the order of administration of these blocks was counterbalanced among participants. Each block consisted of 128 trials, 64 for each time duration. A training block with 40 trials was administered before the experimental blocks. Participants were asked to respond as quickly as possible.

### 2.4. Procedure

Participants were tested in a quiet and isolated room. They wore in-ear plug headphones to reduce environmental noise. The head position was restrained with a chin rest at a viewing distance of 57.7 cm from the screen. All participants had normal or corrected-to-normal vision and were naive to the aim of the study. Participants responded by pressing the "x" or the "m" buttons positioned on the relative left and right side of the computer keyboard, respectively. We asked participants to decide, by pressing a left-hand or a right-hand button, whether a central visual dot (diameter  $2^\circ$ ) had a short- or long-duration (Fig. 1a). In two different sessions, durations were taken from the second/supra-second (1 s, 3 s) or the sub-second (50 ms, 300 ms) range. In each session, in one block of trials, the left button was assigned to short durations and



**Fig. 1** – a) Trial events in Exp 1 with central duration stimuli. b) Trial events in Exp 2 with lateralised duration stimuli (left-side stimulus in the example).

the right to long durations (Compatible Condition). In another block, the assignment was reversed (Incompatible Condition). The order of administration of the Compatible and Incompatible conditions and the sub and supra second range conditions was counterbalanced among participants.

## 2.5. Statistical analyses

The STEARC was measured by comparing the Reaction Times (RTs) advantage in the Compatible versus the Incompatible Condition. In addition, it was also estimated as a function of increasing RTs-length ranked along four quartiles/bins (Rubichi et al., 1997). To examine the temporal dynamics of the STEARC, we used the Vincentization procedure introduced by Ratcliff (1979; see Rubichi et al., 1997; Pinto et al., 2021). For each participant, we calculated the RT distributions of correct responses, i.e., from fastest to slowest, in Compatible and Incompatible trials. We then divided each distribution into four proportional quartiles-bins so that each bin contained the same proportion of trials, i.e., one-fourth of trials. The difference between mean RTs from corresponding bins in Compatible and Incompatible trials, is a bin-by-bin measure of the time course of the STEARC.

In a first analysis, individual RTs were entered in a  $2 \times 2 \times 4$  repeated-measures ANOVA to test the effect of Space–Time Compatibility (Compatible vs Incompatible), Temporal Duration (Short vs Long) and RTs–Bin (Bin 1 vs Bin 2 vs Bin 3 vs Bin 4) as within factors both for the sub- and supra-second range. In all cases, significant interactions were further explored through Bonferroni post-hoc comparisons. Following the method adopted in previous studies (Vallesi

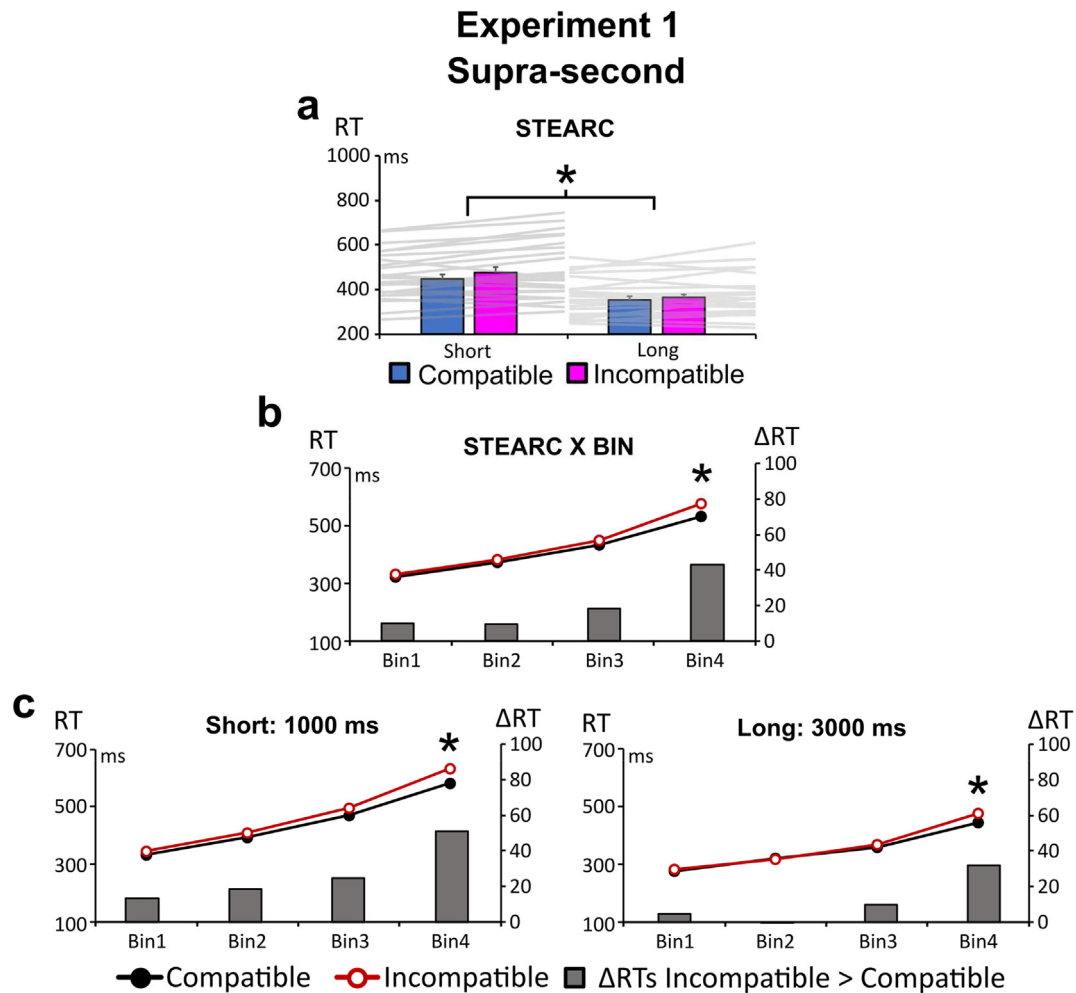
et al., 2008, 2011), RTs shorter than 100 ms and longer than 1500 ms were excluded from the analyses. Following these criteria, 7% of trials were excluded from the analysis. To summarise, Experiment 1 was designed to investigate the development of the STEARC effect as a function of the speed of RTs.

To complement the results of RTs analyses, we entered individual error rates in a series of  $2 \times 2 \times 4$  repeated-measures ANOVA with Space–Time Compatibility (Compatible vs Incompatible), Temporal Duration (Short vs Long) and RTs–Bin (Bin 1 vs Bin 2 vs Bin 3 vs Bin 4) as within factors. Separate ANOVAs were run for each time range from Exp 1. No analysis code was used to perform any of the statistical analyses described in the manuscript.

## 3. Results

### 3.1. Reaction times

In the supra-second range, a significant Space–Time Compatibility effect ( $F(1, 24) = 7.025, p = .014, \eta_p^2 = .226$ ; see Fig. 2a), with faster RTs in Compatible (397 ms) rather than in Incompatible trials (416 ms), demonstrated a significant STEARC. In addition, a significant Space–Time compatibility  $\times$  RTs-bin interaction ( $F(3, 72) = 7.018, p < .001, \eta_p^2 = .226$ ) showed that the STEARC was significant only at the slowest RTs in the fourth bin ( $p < .001$ ; Compatible 513 ms, Incompatible 554 ms; see Fig. 2b). A significant Temporal Duration effect ( $F(1, 24) = 76.110, p < .001, \eta_p^2 = .760$ ; Short 458 ms, Long 354 ms) pointed out a ForePeriod effect.



**Fig. 2** – a) STEARC effect with central duration stimuli in the supra-second range. RTs in the Compatible (blue bars) and Incompatible (magenta bars) Space–Time conditions with short and long durations from the Supra-second time range. Significant STEARC effects are marked with an asterisk (see main text for statistics). Light grey diagonal bars represent individual data trends in the Compatible (left endpoint of the bar) with respect to the Incompatible condition (right endpoint of the bar). (b) STEARC effects in the supra-second range for central stimuli as a function of the speed of RTs: Bin 1 fastest RTs to Bin 4 slowest RTs. Left Y-axis: RTs in the Compatible (black line) and Incompatible (red line) conditions. Right Y-axis: Incompatible minus Compatible RTs difference (grey bars). Significant differences are marked with an asterisk. For descriptive purposes, only panel (c) depicts the time course of STEARC effects with short and long-duration targets.

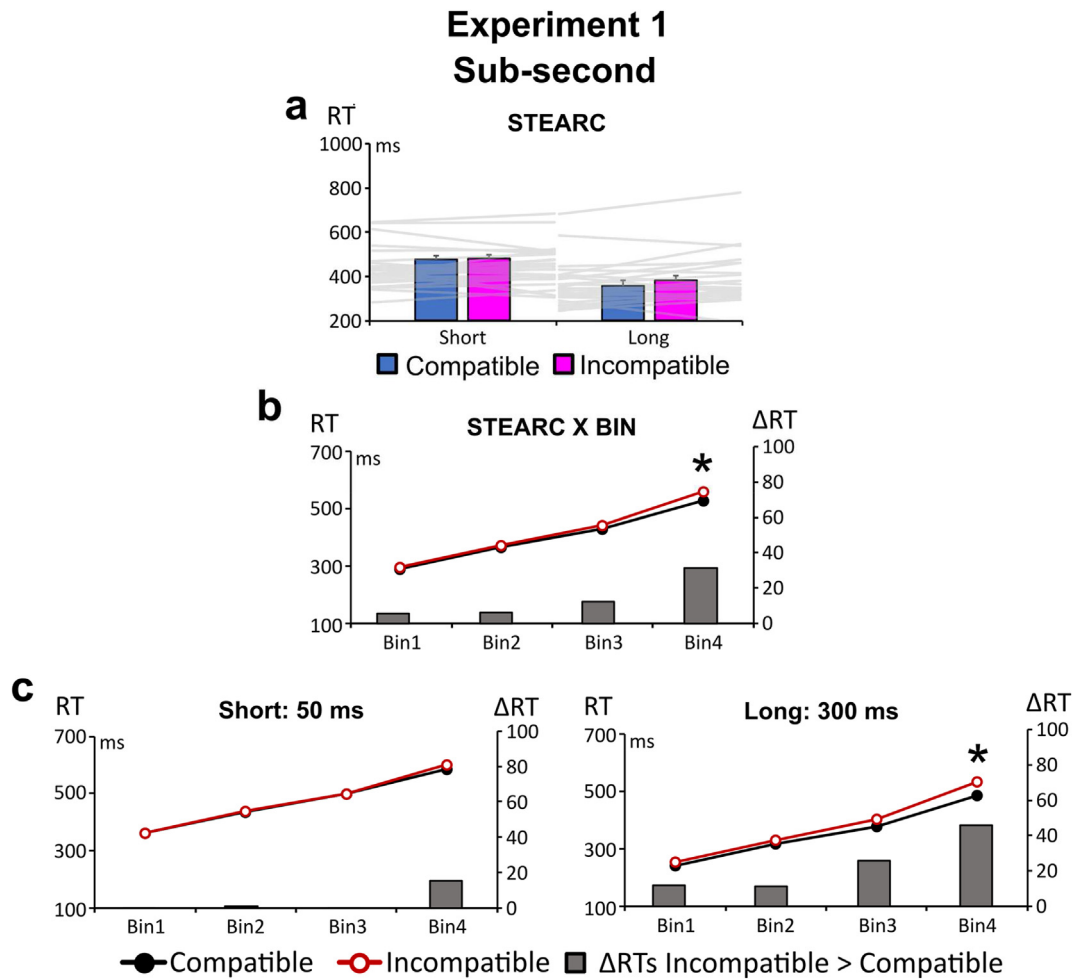
With short durations, a significant interaction between Space–Time Compatibility and RTs-bin ( $F(3, 72) = 4.136$ ,  $p = .009$ ,  $\eta_p^2 = .147$ ) pointed out the STEARC at slowest RTs in the fourth bin ( $p < .001$ ; Compatible 583 ms, Incompatible 634 ms). A similar trend in the presence of the STEARC was also found with long durations ( $F(3, 72) = 2.954$ ,  $p = .038$ ,  $\eta_p^2 = .109$ ; fourth bin:  $p = .007$ ; Compatible 443 ms, Incompatible 475 ms, see Fig. 2c).

In the sub-second range, a significant Space–Time compatibility  $\times$  RTs–Bin interaction was present ( $F(3, 72) = 3.618$ ,  $p = .017$ ,  $\eta_p^2 = .131$ ). This interaction highlighted that, independently of temporal duration, the STEARC was present at the slowest fourth RTs bin ( $p < .001$ ; Compatible 536 ms, Incompatible 567 ms; see Fig. 3b). A significant Temporal Duration effect was also found ( $F(1, 24) = 70.560$ ,  $p < .001$ ,  $\eta_p^2 = .746$ ). This pointed out a conventional ForePeriod effect

(Niemi & Näätänen, 1981) with faster RTs for long duration (367 ms) than short-duration targets (473 ms). Within short durations, no significant interaction between Space–Time Compatibility and RTs-bin was found ( $F(3, 72) = 1.843$ ,  $p = .146$ ,  $\eta_p^2 = 0.071$ ). With the long durations, a significant interaction between Space–Time Compatibility and RTs-bin ( $F(3, 72) = 2.973$ ,  $p = .037$ ,  $\eta_p^2 = .110$ ) showed the presence of the STEARC in the fourth RTs bin ( $p = 0.0001$ ; Compatible 486 ms, Incompatible 532 ms; see Fig. 3c).

### 3.2. Error rate

In the supra-second range, a significant effect of Temporal Duration pointed out a higher percentage of errors with short stimuli;  $F(1, 24) = 13.631$ ,  $p = .001$ ,  $\eta_p^2 = 0.362$ . A significant Bin effect was also found ( $F(3, 72) = 10.560$ ,  $p < .001$ ,  $\eta_p^2 = 0.305$ ).



**Fig. 3** – a) STEARC effect with central duration stimuli in the sub-second range. RTs in the Compatible (blue bars) and Incompatible (magenta bars) Space–Time conditions with short and long-duration targets from the Sub-second time range. Significant STEARC effects are marked with an asterisk (see main text for statistics). Light grey diagonal bars represent individual data trends in the Compatible (left endpoint of the bar) with respect to the Incompatible condition (right endpoint of the bar). (b) STEARC effects in the sub-second range for central stimuli as a function of the speed of RTs: Bin 1 fastest RTs to Bin 4 slowest RTs. Left Y-axis: RTs in the Compatible (black line) and Incompatible (red line) conditions. Right Y-axis: Incompatible minus Compatible RTs difference (grey bars). Significant differences are marked with an asterisk. For descriptive purposes, only panel (c) depicts the time course of STEARC effects with short and long-duration targets.

Bonferroni comparisons showed that the error rate was higher in RTs-bin 3 and 4 with respect to RTs-bin 1 (all  $p < 0.01$ ). We note, as a reminder, that in this case, a general STEARC effect was present with short durations and that the STEARC was significant at the slowest RTs in bin 4 with both short and long durations (Fig. 4).

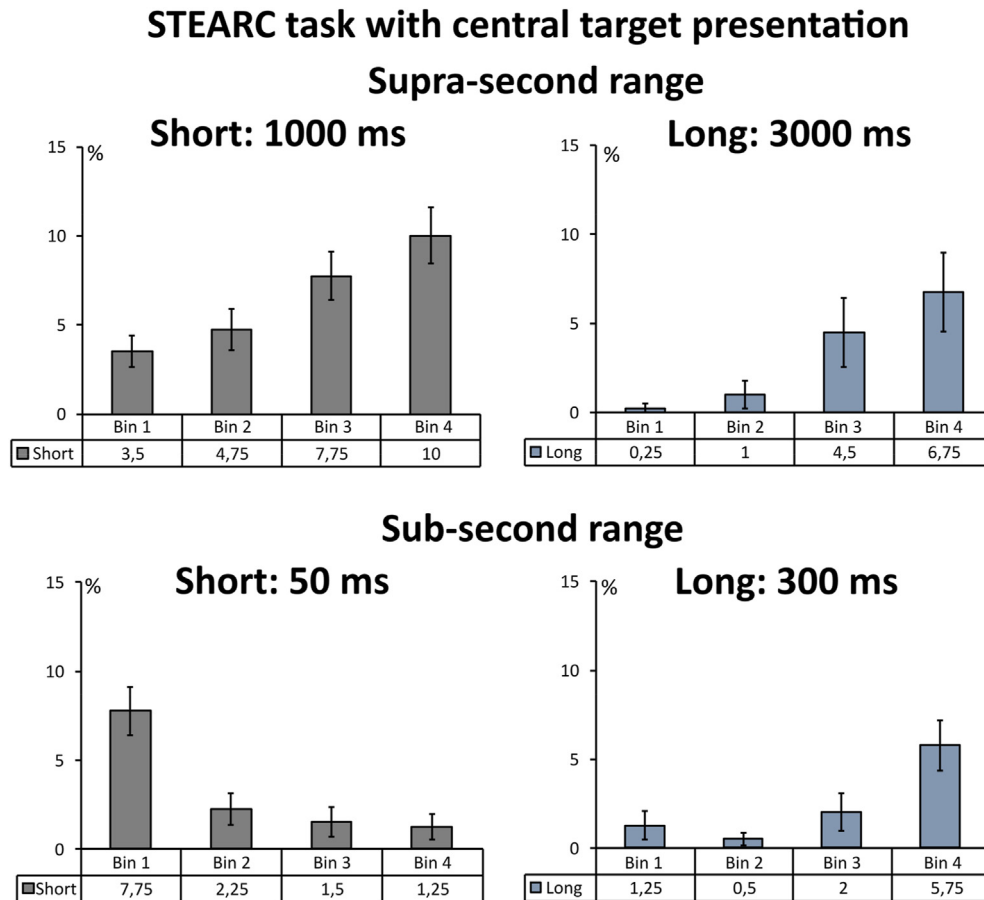
In the sub-second range, we found a significant main effect of RTs–Bin ( $F(3, 72) = 4.647, p = 0.005, \eta_p^2 = .162$ ) and a significant Temporal Duration  $\times$  RTs–Bin interaction ( $F(3, 72) = 13.417, p < .001, \eta_p^2 = 0.358$ ). Bonferroni post-hoc comparisons showed that with short durations when no STEARC was present, the error rate was higher at bin 1 (all comparisons with other bins,  $p < .005$ ). Vice versa, with long durations, when the STEARC was present at RTs-bin 4, the error rate was higher at RTs-bin 4 with respect to RTs-bin 1 and RTs-bin 2 (both comparisons,  $p < .02$ , see Fig. 4).

## 4. Experiment 2

### 4.1. Materials and method

The presentation of stimuli in lateral space produces the automatic coding of their “left” or “right” position (De Jong et al., 1994; Rubichi et al., 1997). The Compatible Condition (with stimulus and response on the same side of space) enhances the automatic coding of the stimulus side, while the Incompatible condition (which requires the selection of a response that is on the side opposite to the stimulus) counteracts the effects of the automatic coding of the target position. The net effect of these processes is the shortening of RTs in the Compatible with respect to the Incompatible condition. Based on this, in Exp 2 we presented the same





**Fig. 4 – Experiment 1: Percentage of response errors as a function of Time Duration and RTs–Bin in the supra-second and sub-second range with central stimuli.**

durations of Exp 1 to the left or the right of central fixation (Fig. 1b) to a new sample of twenty-five participants. We investigated whether, besides introducing conventional compatibility effects between the side of the stimulus and that of the response, forcing the automatic coding of the position of durations sped up their spatial processing and made the STEARC stronger at fast rather than slow RTs, as it occurs when the side of a sensory stimulus is the same as, rather than opposite to that of the response (De Jong et al., 1994; Rubichi et al., 1997).

#### 4.2. Participants

In line with Exp 1, the power analysis (G\*Power program, Faul et al., 2007) showed that 22 participants would be required. Based on this preliminary analysis, we tested a new sample of 26 healthy adult right-handed participants (Exp 2: 18 F and 8 M; mean age: 24.4; data collected in 2021/2022). One participant (M) was excluded from the analyses due to excessive errors (25%).

#### 4.3. Apparatus and stimuli

Experimental materials were equivalent to Exp 1, with the only difference being that, in different trials, stimuli were centred 8° to the left or the right of central fixation (see Fig. 1b).

#### 4.4. Procedure

The procedure of Exp 2 was as that of Exp 1.

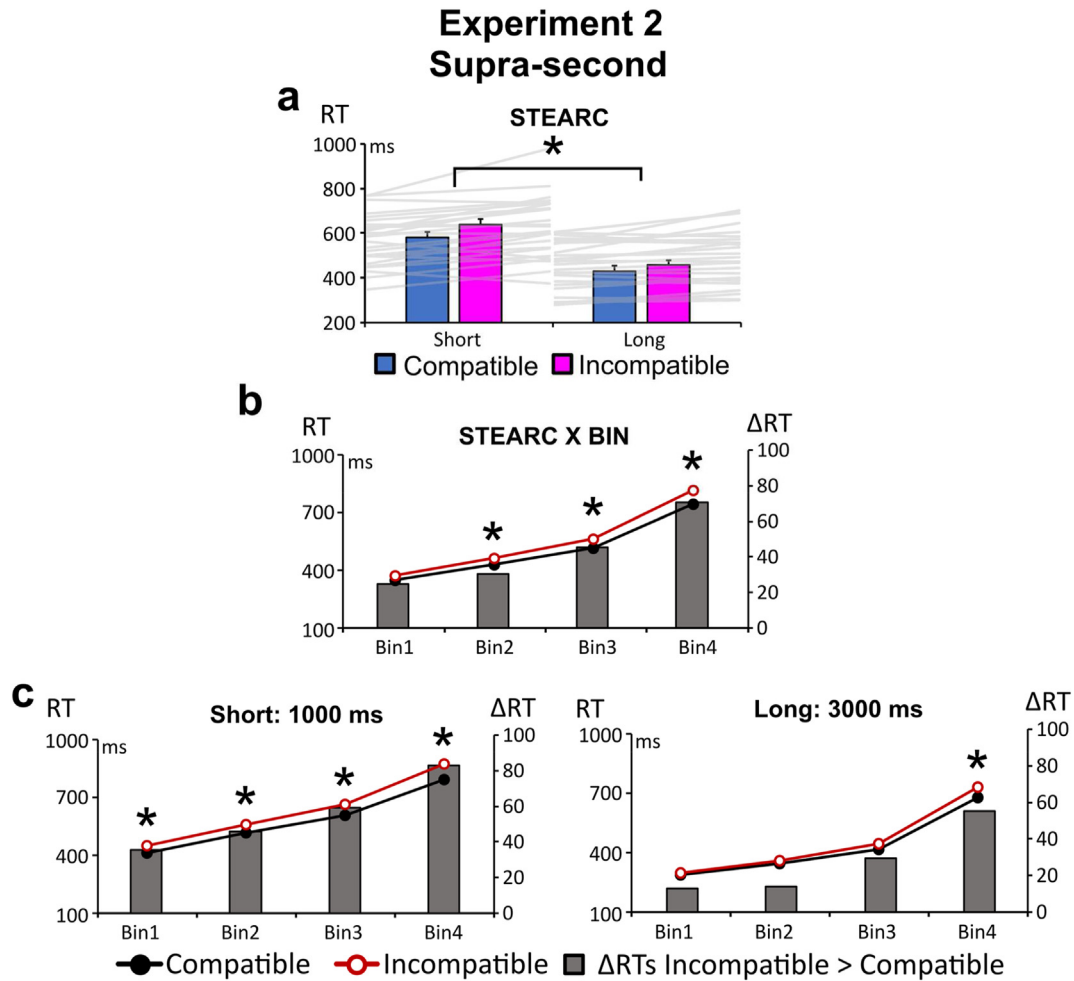
#### 4.5. Statistical analyses

Reaction times and error rates analyses were equivalent to Experiment 1. Following the same criteria used in Experiment 1, 6.3% of trials were excluded from the analysis.

### 5. Results

#### 5.1. Reaction times

In the supra-second range, the Space–Time Compatibility effect was significant ( $F(1, 24) = 22.488, p < 0.001, \eta_p^2 = 0.483$ ; see Fig. 5a). This showed a STEARC with faster RTs in Compatible (505 ms) relative to Incompatible trials (547 ms). In addition, a Space–Time compatibility  $\times$  RTs–Bin interaction ( $F(3, 72) = 5.962, p = 0.001, \eta_p^2 = 0.198$ ) showed that the STEARC was significant from the second to the fourth bin ( $p < 0.05$ ; Compatible 428 ms, 511 ms, 734 ms vs Incompatible 458 ms, 555 ms, 803 ms, see Fig. 5b). A significant Temporal Duration effect ( $F(1, 24) = 123.306, p < 0.001, \eta_p^2 = 0.837$ ; Short 609 ms, Long 444 ms) showed the presence of the ForePeriod

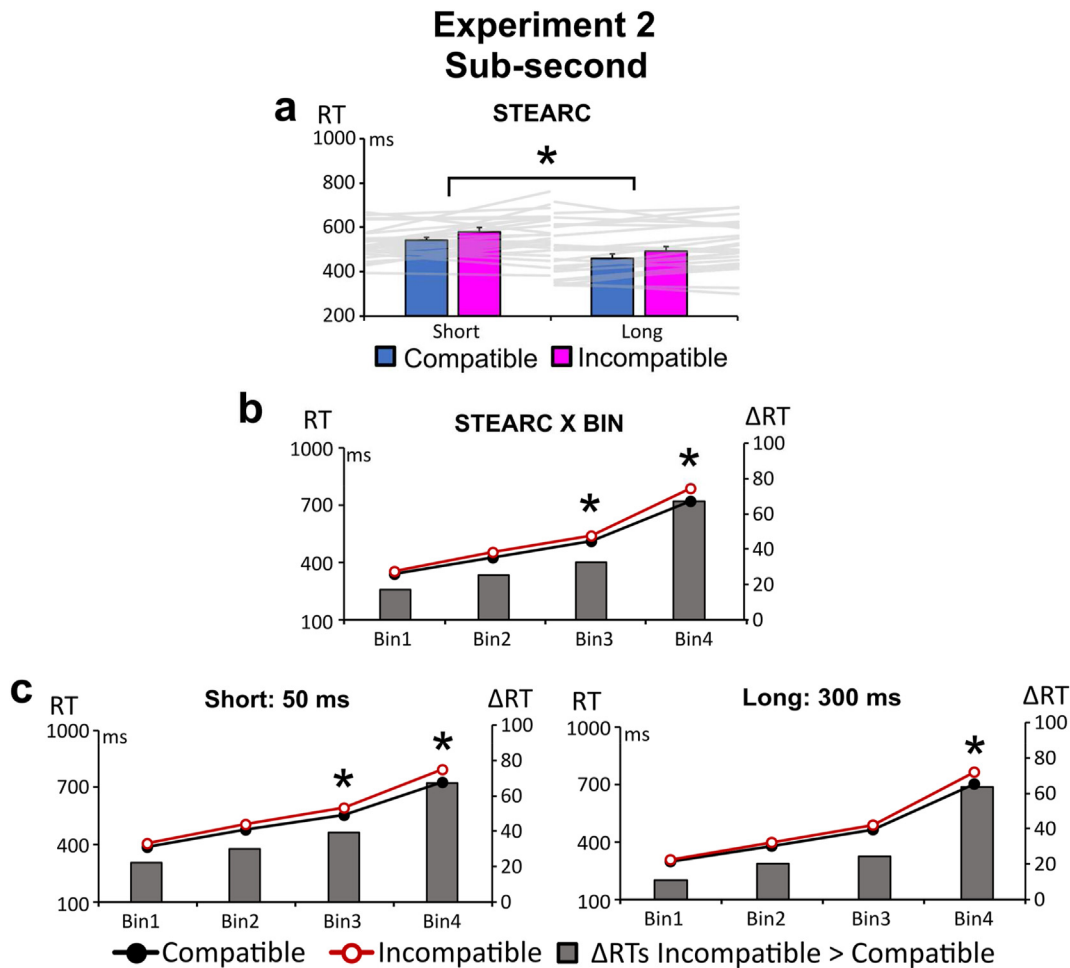


**Fig. 5** – a) STEARC effect with lateralised duration stimuli in the supra-second range. RTs in the Compatible (blue bars) and Incompatible (magenta bars) Space–Time conditions with short and long durations from the Supra-second time range. Significant STEARC effects are marked with an asterisk (see main text for statistics). Light grey diagonal bars represent individual data trends in the Compatible (left endpoint of the bar) with respect to the Incompatible condition (right endpoint of the bar). (b) STEARC effects in the supra-second range for lateralised stimuli as a function of the speed of RTs: Bin 1 fastest RTs to Bin 4 slowest RTs. Left Y-axis: RTs in the Compatible (black line) and Incompatible (red line) conditions. Right Y-axis: Incompatible minus Compatible RTs difference (grey bars). Significant differences are marked with an asterisk. For descriptive purposes, only panel (c) depicts the time course of STEARC effects as a function of short and long target durations.

effect. With short durations, a significant interaction between Space–Time Compatibility and RTs-bin ( $F(3, 72) = 4.982$ ,  $p = 0.003$ ,  $\eta_p^2 = 0.171$ ) showed that the STEARC was present at all RTs-bins and increased as a function of RTs length from bin 1 to bin 4 (bin1: Compatible 411 ms vs Incompatible 447 ms, bin 2: Compatible 514 ms vs Incompatible 560 ms; bin 3: Compatible 606 ms vs Incompatible 665 ms; bin 4: Compatible 791 ms vs Incompatible 874 ms) With long durations, a significant interaction between Space–Time Compatibility and RTs-bin ( $F(3, 72) = 3.547$ ,  $p = 0.018$ ,  $\eta_p^2 = 0.128$ ) highlighted a Compatibility effect at the slowest RTs in the fourth bin ( $p < 0.001$ ; Compatible 676 ms, Incompatible 731 ms, see Fig. 5c).

A significant Space–Time Compatibility effect was found in the sub-second range ( $F(1, 24) = 8.639$ ,  $p = 0.0076$ ,  $\eta_p^2 < 0.264$ ;

see Fig. 6a). This showed a conventional STEARC effect with faster RTs in Compatible (498 ms) than Incompatible trials (533 ms). In addition, a significant Space–Time compatibility  $\times$  RTs–Bin interaction ( $F(3, 72) = 5.476$ ,  $p < 0.001$ ,  $\eta_p^2 = .185$ ) highlighted the presence of the STEARC only at the third and fourth RTs-bins ( $p < 0.05$ ; third bin: Compatible 509 ms vs Incompatible 540 ms, fourth bin: Compatible 715 ms vs Incompatible 780 ms see Fig. 6b). A significant Temporal Duration effect ( $F(1, 24) = 35.823$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.598$ ; Short 557 ms, Long 473 ms), showed the presence of the ForePeriod effect. With short durations, the interaction between Space–Time Compatibility and RTs-bin was significant ( $F(3, 72) = 4.442$ ,  $p = 0.006$ ,  $\eta_p^2 = 0.156$ ). This demonstrated the presence of the STEARC in the third and fourth RTs-bins ( $p < 0.001$ ; third bin: Compatible 555 ms vs



**Fig. 6** – a) STEARC effect with lateralised duration stimuli in the sub-second range. RTs in the Compatible (blue bars) and Incompatible (magenta bars) Space–Time conditions with short and long durations from the Sub-second time range. Significant STEARC effects are marked with an asterisk (see main text for statistics). Light grey diagonal bars represent individual data trends in the Compatible (left endpoint of the bar) with respect to the Incompatible condition (right endpoint of the bar). (b) STEARC effects in the sub-second range for lateralised stimuli as a function of the speed of RTs: Bin 1 fastest RTs to Bin 4 slowest RTs. Left Y-axis: RTs in the Compatible (black line) and Incompatible (red line) conditions. Right Y-axis: Incompatible minus Compatible RTs difference (grey bars). Significant differences are marked with an asterisk. For descriptive purposes, only panel (c) depicts the time course of the STEARC effect with short and long-duration targets.

Incompatible 595 ms; fourth bin: Compatible 727 ms. vs Incompatible 794 ms). In the case of long durations, a significant Space–Time Compatibility by RTs-bin interaction ( $F(3, 72) = 2.880, p = 0.041, \eta_p^2 = 0.107$ ), showed that the STEARC was present at the slowest RTs in the fourth bin ( $p < 0.001$ ; Compatible 702 ms, Incompatible 766 ms, see Fig. 5c).

To summarise, lateralising duration targets in Exp 2 did not reverse or change the progressive increase of the STEARC as a function of RT length.

## 5.2. Error rate

In the supra-second range, no bin effect was found with short durations when a significant STEARC was present. With long durations, when the STEARC effect was present and significantly increased at bin 4 ( $F(3, 72) = 11.579, p < .001, \eta_p^2 = .325$ ), Bonferroni comparisons showed that the error rate increased at bin 4 with respect to all other bins ( $p < .001$ , Fig. 7).

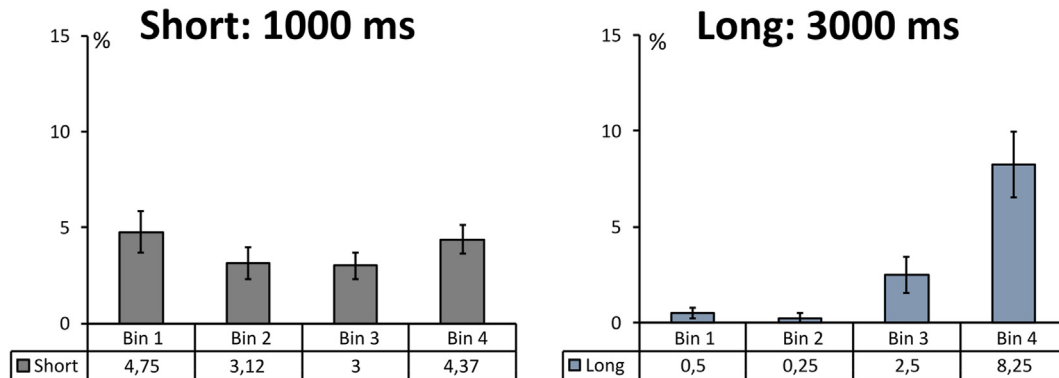
In the sub-second range, there was a significant Temporal Duration  $\times$  RTs–Bin interaction ( $F(3, 72) = 5.746, p < .001, \eta_p^2 = .193$ ). Bonferroni comparisons showed no bin effects with short durations when both a general STEARC effect was present and a significant increase of the STEARC was present at bins 3 and 4. A significant bin effect was found with long sub-second durations when both a general STEARC effect and a significant increase of the STEARC at bin 4 were present. Bonferroni comparisons showed that the error rate was significantly higher at bin 4 with respect to all other bins ( $p < .02$ , Fig. 7).

To summarise, the error rate analysis suggests that, in both experiments, when a significant STEARC is present, the error rate is stable or increases as a function of RTs length, particularly at the slowest RTs in bin 4. This suggests that the late spatial coding of time does not improve and can be even detrimental to performance with respect to the non-spatial coding of time at shorter RTs.

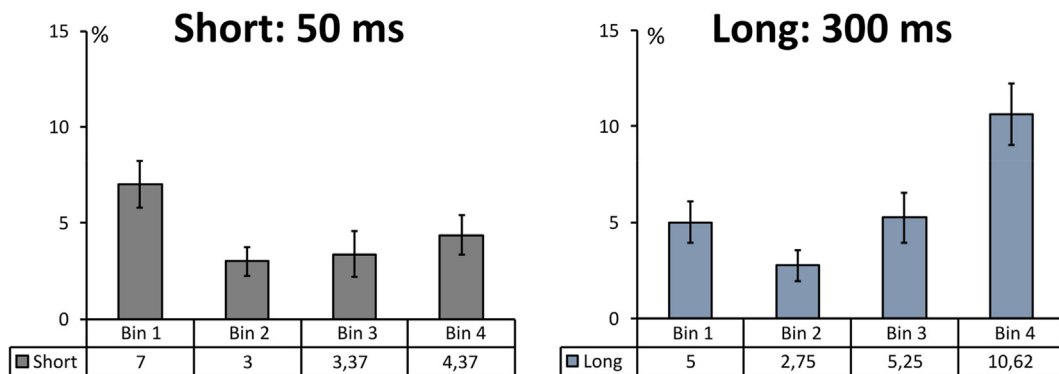


## STEARC task with lateralized target presentation

### Supra-second range



### Sub-second range



**Fig. 7 – Experiment 2–Percentage of response errors as a function of Time Duration and RTs–Bin in the supra-second and sub-second range with lateralised stimuli.**

## 6. Discussion

The main purpose of the present study was to investigate whether the significance and strength of the STEARC effect vary as a function of the speed of RTs. To this aim, the STEARC was analysed across consecutive RTs bins. Our experiments show that it takes time to frame the flow of time in a nurture-dependent left-to-right oriented spatial representation. In addition, when the STEARC was measured in the conventional supra-second range, response errors increased as a function of RT length, which suggests that the spatial coding of time introduces cognitive costs. In contrast, in the same temporal range, the absence of the STEARC at short RTs shows that the brain can take fast and accurate temporal decisions without using spatial heuristics derived from reading and scanning habits. In short, the brain needs time to let nurture take over nature in time processing. In the sub-second range, a significant STEARC was observed only at the longest RTs in bin 4 and with longer 300 ms duration. The absence of the STEARC with very short 50 ms durations supports the idea that the spatial representation of time is a late cognitive event with no time to take place when a sensory event is extremely short.

The brain computes time by coding monotonic increases or decreases in neuron firing rate or by monitoring the changing pattern of activity of neurons in a network (Zhou & Buonomano, 2022). Psychophysical, psychopharmacological, brain imaging and neurocomputational studies have suggested that brain mechanisms dedicated to processing sub- and supra-second time durations are not entirely overlapping (Hayashi et al., 2014; Nani et al., 2019; Paton & Buonomano, 2018; Rammsayer et al., 2015). Generally, more automatic sensory-motor mechanisms for sub-second durations get progressively integrated and controlled by attentional and working-memory mechanisms in estimating supra-second durations. A partial dissociation between these two mechanisms is also provided by behavioural evidence showing that while a concurrent non-temporal secondary task impairs the discrimination of second-to-supra-second time intervals, it does not affect that of 50–100 ms intervals (Rammsayer & Lima, 1991; Rammsayer & Ulrich, 2011). In the same vein, the administration of pharmacological agents that interfere with working memory disrupts the processing of supra-second duration though not that of sub-second ones (Rammsayer and Ulrich, 2011). Brain imaging studies pointed

out the involvement in time processing of subcortical, i.e., striatum, cerebellar and cortical structures like the SMA, the parietal lobe and the prefrontal cortex (Ivry & Keele, 1989; Lewis & Miall, 2003; Nani et al., 2019; Protopapa et al., 2019; Wiener et al., 2011). Meta-analyses of brain imaging evidence corroborate the idea that some cortical mechanisms take over subcortical and cerebellar ones as time durations increase, shifting towards cognitively controlled forms of processing (Nani et al., 2019). For example, a recent investigation in rats showed that pharmacological inactivation of the lateral cerebellar nucleus does not impair the discrimination of supra-second durations (Heslin, 2022). In line with the idea of a correspondence between the anatomo–functional transition from “sensory-motor” to “cognitive” mechanisms of time coding and the transition from the processing of short sub-second to long supra-second durations, our findings show that when a stimulus is very short, i.e. 50 msec, or when the responses to longer sub-second 300 ms and supra-second 1 and 3 s duration are fast, no spatial coding of time takes place. In other words, in the STEARC task, it takes time for cognitive spatial codes that regulate the selection of the appropriate motor response to generate or get in touch with an equivalent mental spatial organisation of time flow.

The set of findings reported in our investigation provides clues for a number of theoretical and empirical issues. First, since in our task, the slow spatial coding of time introduces cognitive costs, as pointed out by an increase of errors in the classification of time durations at slower RTs, one might wonder which are the functional advantages of spatial coding. It has been argued that spatial-directional gestures that conform to sensorimotor or cultural habits are spontaneously adopted to communicate and share temporal concepts with human conspecifics. As an example, the concept of the “past” is conveyed with a backward or leftward waving of the hands and the concept of “future” with forward or rightward waving (Núñez & Sweetser, 2006; Casasanto and Bottini, 2014). These observations suggest that in social contexts where clarity of communication is more important than the speed of spatial-motor choices, like those required in the STEARC task, the spatial coding of time probably reaches its peak of functional and adaptive value. Based on the finding that the pace/number of finger tappings modifies perceived numerosity and time duration, with fast tapping producing underestimation and slow tapping overestimation, Anobile et al. (2021) have recently suggested that these effects arise from a dedicated brain sensorimotor system that interfaces action with the sensory processing of quantitative magnitudes such as space and time. Our findings show that programming and selecting a left vs a right motor response extends its effect beyond sensory perception and affects the mental representation of time flow by providing it with a left-to-right organised spatial envelope. Nonetheless, and most importantly, the same findings show that this is a late mechanism that interfaces action selection with time representation, a mechanism that gets progressively superimposed on an early, non-spatial and autonomous mechanism of time estimation.

Second, the STEARC has been found not only during the discrimination of time durations but also during the

semantic classification of words indicating the past or the future (Santiago et al., 2007). Based on this finding, it is to wonder whether an RT-bin effect like the one we observed in the present study will also likely be found during the semantic classification of past and future words. Behavioural findings suggest that the semantic processing of time-words seems to engage slower decisional-cognitive mechanisms (average RTs higher than 700 ms in Santiago et al., 2007) than the processing of time durations (average RTs in Experiment 1 of our study = 400 ms). Based on these results, one could reasonably hypothesise that STEARC is already found at fast RTs during time-word classification, that is, at RTs that are slower than those recorded during judgments of time durations: this is an interesting point that deserves further investigation. Finally, extending our observations to other sensory domains would be interesting. For example, in a task requiring the comparison of time intervals between consecutive brief acoustic clicks, Ishihara et al. (2008) reported a descriptive relationship between the amplitude of the STEARC and the speed of individual RTs: future studies might further expand the inquiry in the acoustic domain by using the within-participant analyses of the time course of the STEARC adopted in the present study.

In our set of data, there is another feature that might be consonant with the functional partition between mechanisms dedicated to the monitoring of very short sub-second vs longer or supra-second time durations. As already pointed out in the discussion, when in Experiment 1, a conventional STEARC was present, errors in performance grew as a function of RTs (and STEARC strength). In contrast, with very short 50 ms durations, when no STEARC was found independently of RT length, performance error peaked at the fastest RTs in the first bin rather than at the slowest RTs in the fourth bin.

Developmental studies show that in western participants, the left-to-right representation of time gradually makes its appearance at 5 years of age (Tillman et al., 2020) and stabilises at 8–10 years of age “as a fruit of learning” (Droit-Volet & Coull, 2015). Our findings demonstrate that the behavioural effects linked to the nurtured and slow spatial coding of time can be separated from those linked to the fast non-spatial coding: we think that the possibility of drawing this empirical separation can importantly renew and enrich the understanding of the functional and anatomical interaction among brain mechanisms that are dedicated to the processing of time, space and numbers (Walsh, 2003). It remains now to be seen whether the spatial coding of time depends on the use of spatial response codes in the task at hand or whether it also takes place when no use of these codes is required (Anelli et al., 2018; Pinto et al., 2019, 2021).

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### Author contributions

F.D, G.S., and M.P developed the study concept. All authors contributed to the study design. G.S., M.P., S.L. and S.L. collected and analysed data. F.D., M.P. M.Paton and N.B. drafted the manuscript. All co-authors provided critical revisions to the initial version of the manuscript.

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## Data accessibility

We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study. No part of the study or analyses procedures were pre-registered prior to the research being conducted.

The conditions of our ethics approval do not permit public archiving of anonymised study data. Readers seeking access to the data should contact the corresponding author Prof. Fabrizio Doricchi ([fabrizio.doricchi@uniroma1.it](mailto:fabrizio.doricchi@uniroma1.it)) or the local Ethical Committee of the Department of Psychology, Roma–Italy. Access will be granted to named individuals in accordance with ethical procedures governing the reuse of sensitive data. There are no specific conditions that the requestors must meet to obtain the data. Experimental digital materials, stimuli and code relative to the experiment described in this manuscript are available on Open Science Framework following this link: <https://osf.io/rx56y/>

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## Credit author statement

**Gabriele Scozia:** Conceptualization, Software, Methodology, Investigation, Data Curation, Formal analysis, Writing Original Draft, Writing- Reviewing and Editing. **Mario Pinto:** Conceptualization, Methodology, Investigation, Formal analysis, Writing-Review & Editing. **Silvana Lozito:** Software. **Stefano Lasaponara:** Writing-Review & Editing, Resources. **Nicola Binetti:** Writing-Review & Editing. **Mariella Pazzaglia:** Writing-Review & Editing. **Fabrizio Doricchi:** Conceptualization, Methodology, Supervision, Writing-Original Draft, Writing- Reviewing & Editing, Funding acquisition and Project Administration.

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