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Exploring spatiotemporal interactions: On the superiority of time over space

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Abstract

Space and time mutually influence each other such that space affects time estimation (space-on-time effect), and conversely (time-on-space effect). These reciprocal interferences suggest that space and time are intrinsically linked in the human mind. Yet, recent evidence for an asymmetrical advantage for space over time challenges the classical theoretical interpretation. In the present study, we tested whether the superiority of space over time in magnitude interference depends on the cognitive resources engaged in the spatial task. We conducted three experiments in which participants performed judgments on temporal intervals and spatial distances in separate blocks. In each trial, two dots were successively flashed at various locations, and participants were to judge whether the duration or distance between the dots was short or long. To manipulate cognitive demands in the spatial task, distances varied across experiments (highly discriminable for the non-demanding spatial task in Experiment 1 and scarcely discriminable for the demanding spatial task in Experiment 2). Importantly, this manipulation tended to enhance perceptual sensitivity (as indexed by Weber Ratios) but slowed down the decision process (as indexed by response times) in the demanding experiment. Our results provide evidence for robust space-on-time and time-on-space effects (Experiments 1 and 2). More crucially, the involvement of cognitive resources in a demanding spatial task causes a massive time-on-space effect: Spatial judgments are indeed more influenced by irrelevant temporal information than the reverse (Experiments 2 and 3). Overall, the flexibility of spatiotemporal interferences has direct theoretical implications and questions the origins of space-time interaction.

Keywords Space-time interference · Response times · Cognitive resources · Sequential sensory information · Magnitude processing

Introduction

Space and time are intrinsically linked in the visual world. In everyday activities, such as when catching a ball, the cognitive system needs to accurately process spatial distance to anticipate the right location, as well as the temporal interval to predict the moment when one should catch the ball. Efficient processing of both spatial and temporal information on the basis of visual information is crucial to appropriately interact with the surroundings. A theory developed by Walsh (2003 - AToM) suggests that magnitudes such as space, time, and number are represented by common processing mechanisms, underlying a generalized magnitude system (also see Bueti & Walsh, 2009, de Hevia et al., 2014). Within the AToM framework, one of the major arguments arises from behavioral interactions between spatial, temporal, and numerical magnitudes. Numerous studies have provided evidence for spatiotemporal interference. Judgments of stimulus duration or temporal interval between two stimuli are critically influenced by the spatial characteristics of the stimuli (referred to as the space-on-time effect; Cohen et al., 1953). Specifically, the longer the distance, the longer the perceived duration is. The effects of space on time have been extensively investigated and replicated (Bausenhart & Quinn, 2017; Kliegl & Huckauf, 2014; Kuroda & Grondin, 2013; Kuroda et al., 2016; Roussel et al., 2009; for a review, see Grondin, 2010). Reciprocally, spatial estimates can also be influenced by the temporal characteristics of the stimulus (referred to as the time-on-space effect; Helson & King, 1931), so much so that the longer the duration, the longer the perceived covered distance. The assumption that magnitude interferences are reciprocal and symmetrical has been challenged as a series of studies has found that space modulates temporal estimates, and not the other way around (Casasanto & Boroditsky, 2008). Temporal information does not substantially interfere with spatial (or numerical) estimates (Bottini & Casasanto, 2013; Cai et al., 2013;

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Casasanto et al., 2010; Coull et al., 2015; Dormal & Pesenti, 2013; Magnani et al., 2014; Merritt et al., 2010; Starr & Brannon, 2016; Vicario et al., 2008; Xuan et al., 2007; Xue et al., 2014; for a review, see Loeffler et al., 2018). In a seminal study conducted by Casasanto and Boroditsky (2008), a convincing series of experiments suggest that time-on-space interference is unreliable and weak, or even inexistent. Spatial estimates were indeed poorly affected (or even unaffected) by the temporal characteristics of the to-be-judged stimulus, while temporal estimates were drastically influenced by irrelevant spatial characteristics of the to-be-judged stimulus (i.e., long lines were perceived as lasting longer on the screen). The Conceptual Metaphor Theory assumes that concrete spatial terms are used to overcome the abstract nature of time. Humans may use spatial markers to mentally represent temporal knowledge such as duration but also past and future events (Casasanto & Boroditsky, 2008). Space would play a predominant role in time perception.

Yet, one could wonder whether the superiority of space over time could be an artefact, stemming from differences in cognitive demands across the spatial and temporal tasks. Temporal tasks used in this literature are often much more difficult and more resource-demanding than spatial ones, thus entailing less precise but effortful judgments. The objective of this study was to directly test whether and how the cognitive resources engaged in spatial and temporal processing impact spatiotemporal interference. In a recent attempt to match difficulty across tasks, stimulus intensities and ratios were carefully calibrated to obtain similar perceptual thresholds in the spatial and temporal tasks. Since magnitude processing is characterized by the Weber law, according to which accuracy depends on the ratio of the magnitudes to be compared rather than on the absolute intensity difference, researchers assumed that experimental tasks were equally difficult whenever Weber ratios (WRs) – or accuracy – are similar (Coull et al., 2015; Martin et al., 2017). However, recent papers smartly underlined that WRs alone cannot fully characterize the decision process in a magnitude discrimination task given that the temporal dynamics of the decisional process are neglected (Balci & Simen, 2014; Brus et al., 2019; Link, 1992; Pardo-Vazquez et al., 2019; Simen et al., 2016). Indeed, discriminability can independently affect WRs and RTs (Simen et al., 2016). They suggest incorporating response times (RTs) to further define the discrimination process and to inform about task difficulty as well as about the level of cognitive resources engaged in a task.

In the present study, we aimed to revisit spatiotemporal interference by considering the temporal dynamics of the decision process. Our objective was to tackle the issue that response times could inform about the discrimination process in the context of interference. In three experiments, performance in the spatial and temporal tasks was assessed with well-known indexes of perceptual discrimination and sensitivity (Point of Subjective Equality – hereafter PSE and WRs) and also with an index of the decisional process (RTs). We hypothesized that (i) the space-on-time effect is more pronounced when the spatial task does not require sustained cognitive resources, as revealed by low WRs and more importantly by short RTs (Experiment 1); and that (ii) the time-on-space effect is reliable and massive when cognitive demands in the spatial task increase, characterized by long RTs (Experiment 2). Finally, in Experiment 3, we replicated this finding in a within-subject design, corroborating that the time-on-space effect is reliable and depends on cognitive resources engaged in the spatial task.

Experiment 1: Non-demanding spatial task

The goal of Experiment 1 was to replicate the advantage of space over time in spatiotemporal interactions (Casasanto & Boroditsky, 2008; Coull et al., 2015; Magnani et al., 2014; Martin et al., 2017). In two different blocks, participants performed either temporal or spatial judgments while ignoring irrelevant spatial or temporal information, respectively. We used a bisection procedure[1] in which participants are familiarized with a short and a long reference duration and then asked to judge whether intermediate durations are closer to the short or long reference duration (see Allan & Gibbon, 1991; Church & Deluty, 1977; Meck, 1983; Penney & Cheng, 2018). This procedure was also adopted for spatial judgments. Spatial distances (reference and intermediate distances) were similar in terms of lengths and ratios to those commonly used in the literature (hereafter referred to as the *non-demanding condition* –for more details, see the *Stimuli and procedure* section). We expected the space-on-time effect to be larger than the time-on-space effect, as already reported in the literature (Cai et al., 2018; Casasanto & Boroditsky, 2008; Coull et al., 2015). Furthermore, PSE, WRs, and RTs were analyzed. Given the spatial distances used here, we expected the spatial task to be less demanding in terms of cognitive resources than the temporal one. As a consequence, perceptual sensitivity should be higher (lower WRs) and the decision process faster (shorter RTs) in the spatial task.

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[1] Note that in the context of a reproduction task, a bisection procedure consists of the reproduction of the "half" duration of a visually or auditorily presented stimulus (e.g., Mioni et al., 2014). In a perceptual task, the bisection procedure uses dichotomic response. Participants are to categorize a stimulus duration as closer to either a short or a long reference they had previously been familiarized with. This perceptual temporal bisection procedure has been extensively used in the literature (see Church & Deluty, 1977; and more recent studies, for instance Balci & Simen, 2014; Mioni et al., 2015; Mioni et al., 2018).

Methods

Participants

A total of 19 participants (including 13 women; 13 right-handed) between 17 and 48 years of age (mean 23.25, SD 8.10) participated in this study. Sample size was determined using effect sizes from previous research examining space-time interference (Starr & Brannon, 2016; effect size $f = .80$, with power ($1 - ß$ err prob) = .95, and $\alpha = .05$), for a main experimental design that has two within-subjects factors and one between-subjects factor (G*Power, Faul et al., 2007). All the participants, who were recruited from the Université Paul Valéry Montpellier (France), gave their written informed consent. The study was carried out according to the principles of the Declaration of Helsinki and in accordance with the Department of Psychology Ethics Committee guidelines (Université Paul Valéry Montpellier). All reported to have normal or corrected-to-normal vision.

Apparatus

A PC (Acer Aspire 5742) running E-Prime 2.0 software (Schneider et al., 2002) controlled stimulus presentation, timing operations and data collection. Stimuli were presented on a 15.6-in. computer screen (1,366 × 768 pixels, 60 Hz). Manual responses were collected by clicking on the left and right buttons of the touchpad with the participants' right hand.

Stimuli and procedure

Participants were tested individually in a dimly lit room and sat at an approximate distance of 57 cm from the computer screen. All participants were to complete bisection tasks with temporal intervals and spatial distances in two consecutive sessions, which were counterbalanced between participants. Bisection protocols were initially developed in animal research on timing and then adapted to adult human participants (see Wearden, 1991). Every trial started with a fixation cross, subtended a 0.5° visual angle, for 1,000 ms. Thereafter, two stimulus displays separated by an empty black background were successively flashed. A response display, presenting a grey-colored question mark on a black background, remained on the screen until response within the maximum time limit of 5,000 ms. While stimulus display presentation was set at 300ms, the duration of the empty black background varied from 100 to 600 ms in five steps (100, 225, 350, 475, and 600 ms). Stimulus display was composed of a grey dot (0.8° in diameter) displayed on a black background. Dot location was manipulated on the horizontal plane. For the first stimulus display, the dot could be at one out of two possible locations (left- and a right-sided at 1.6° from the center). So as to manipulate covered distance between the two dots, the second dot could be positioned at five possible locations according to the starting position (first dot). The successive presentation of the two dots gave rise to apparent motion percepts, in the sense that the dot seemed to travel either leftward or rightward (see Fig. 1).

Depending on the task at hand, participants had to judge either the *covered distance* or the *elapsed time* separating the two dots as rather short or long by pressing a response key. Response mapping was counterbalanced between participants. In this experiment, covered distances were clearly distinguishable from one another since dots were separated by 1.6° for the shorter distance and by 12.8° for the longer one (2.8° gap between consecutive distances; 1.6°, 4.4°, 7.2°, 10.0°, and 12.8°; see Fig. 1, Panel B). Participants first received instructions about the experimental tasks and were presented twice with the short and long durations (100 and 600 ms) and then twice with the short and long distance (1.6° vs. 12.8°). In the second step, participants were familiarized with either the two temporal or the two spatial anchors depending on session order. Participants performed 12 training trials whose procedure was identical to that of experimental trials, except that feedback was provided (1,500 ms). For the experimental block, participants were informed that intermediate durations or distances would be inserted. As a result, they were to judge whether the current duration or distance between the dots was closer to the shorter or longer anchors previously learned.

To elicit time-space interference during the spatial task in which five distances were judged (relevant dimension), the elapsed time between dots was also manipulated (referred to as the irrelevant dimension here). Two temporal anchors were used, so that a 100- or 600-ms gap separated the two dots. Conversely, when elapsed time was relevant to the task (temporal task), two irrelevant distance anchors were used to produce space-on-time interference (1.6° vs. 12.8°). Each of the separate spatial and temporal tasks consisted of one block of 100 trials. The relevant dimension was divided into five levels (five distances in the spatial task and five durations in the temporal task) and the irrelevant dimension in two levels (two durations in the spatial task and two distances in the temporal task). Every experimental condition was repeated 10 times within a block. Participants therefore completed 24 training trials and 200 experimental trials.

Data analyses

In the three experiments reported here, we collected the proportion of "long" responses (P(long)) and mean response times (RTs) for each participant. To further explore potential perceptual distortions, PSE were computed from the P(long) data. Indeed, to further analyze interference effects in the three

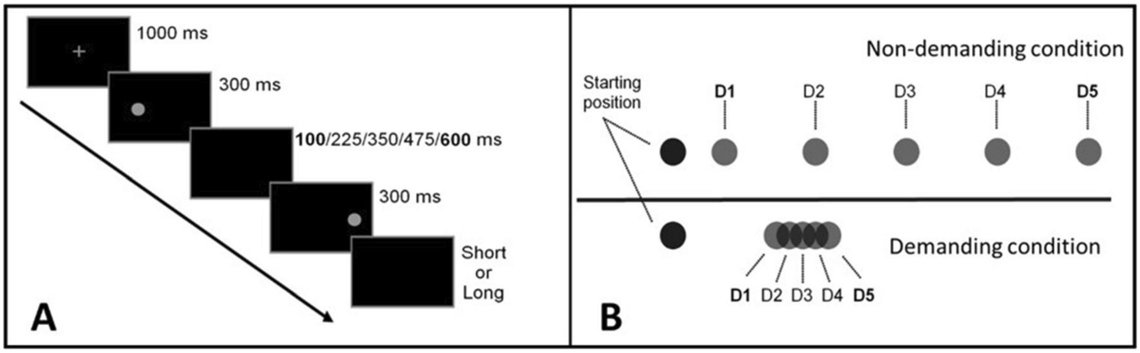

Fig. 1 **Panel A** represents a schematic trial design and **Panel B** represents the different dot positions as a function of the experiment: "non-demanding condition" for Experiment 1, and "demanding condition" for Experiment 2

experiments, we calculated the PSE for each participant in every experimental condition. Each PSE value was calculated from a slope and an intercept, obtained by fitting the psychometric raw data with the Pphy package on R (R Core Team, 2014). Pphy is an R package that uses the modelfree package to obtain a "per subject local linear fitting" (Żychaluk & Foster, 2009), which was included as a random effect to account for the repeated-measure nature of the design as well as individual differences in response scale use. The slope, the PSE and the JND (just-noticeable difference) were extracted per subject and condition. PSE represents the theoretical value in which the probability to judge a distance or duration as being long is 0.5. A low PSE value refers to an overestimation, and a high PSE value to an underestimation. In Experiments 1 and 2, given that participants performed two tasks (spatial and temporal) and were presented with two irrelevant magnitudes (two durations for the spatial task and two distances for the temporal task), four PSE values were calculated for each participant (2 Tasks × 2 Irrelevant magnitudes). To analyze and compare irrelevant magnitude (space-on-time and time-on-space effects) on a comparable scale, PSE values were standardized by subtracting mean and dividing by standard deviation. The standardization was performed per condition and task. In Experiment 3, the participants only performed a spatial task while distance discriminability was manipulated. Four PSE values were calculated for each participant given the two "discriminability" conditions (non-demanding and demanding) and the two irrelevant temporal magnitudes. PSE values were standardized, by subtracting mean and dividing by standard deviation, per condition to lay stress on the effect of irrelevant magnitude (i.e., time-on-space effect).

Additionally, to assess perceptual sensitivity, WRs were computed separately for the spatial and temporal tasks in the three experiments. As mentioned in the *Introduction*, WRs index perceptual sensitivity. It is computed by dividing the just-noticeable difference (JND) by the PSE.

Results

The data from three participants were removed from statistical analyses due to extremely low performance on the anchors (shorter and longer durations or distances) in the two tasks for two of them and in the temporal task for the third participant. The final sample included 16 participants.

To explore perceptual sensitivity, we performed a repeated-measures ANOVA on WRs with the variables Task (Spatial, Temporal) and Irrelevant magnitude (short or long distance/duration, depending on the task) manipulated within participants. This analysis showed a main effect of Irrelevant magnitude ($F(1, 15) = 11.21$, $p = .004$, $\eta^2 p = .43$), but no significant main effect of Task ($F(1, 15) = 1.15$, $p > .05$, $\eta^2 p = .07$). The interaction Task × Irrelevant magnitude was significant ($F(1, 15) = 12.47$, $p = .003$, $\eta^2 p = .45$), suggesting that WRs increased in the temporal task when travelled distance was long. These results suggest that WRs were not fully similar in the two tasks, with a slight advantage for the spatial task (see Table 1).

To test spatiotemporal interferences, we then performed a repeated-measures ANOVA on standardized PSE value with the variables Task (Spatial and Temporal) and Irrelevant magnitude (short or long distance/duration, depending on the task) manipulated within participants.[2] The results showed a main effect of Irrelevant magnitude ($F(1, 15) = 20.48$, $P < .001$, $\eta^2 p = .58$) and, as expected, a significant interaction Irrelevant magnitude × Task ($F(1, 15) = 6.32$, $p = .024$, $\eta^2 p = .30$), revealing that the space-on-time effect was higher than the time-on-space effect (see Figs. 2 and 3).

Lastly, we performed a repeated-measures ANOVA on mean RTs with the variables Task (Spatial, Temporal), Relevant magnitude (the five levels of distance or duration,

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[2] As PSEs were standardized per task, the main effect of Task was disregarded.

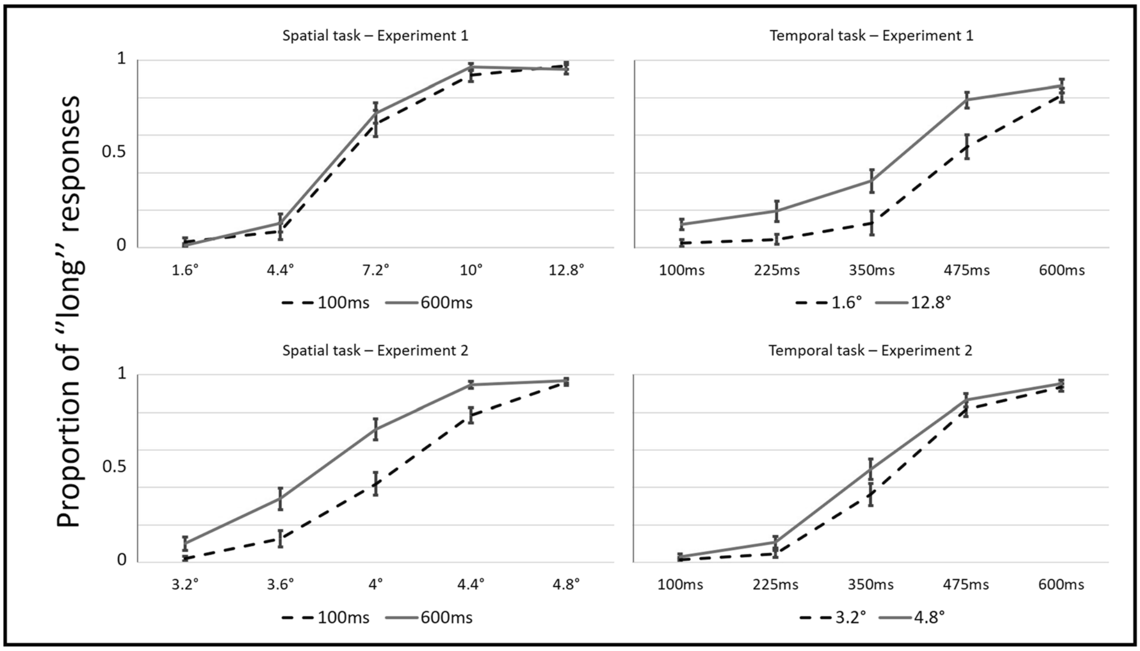

Fig. 2 The proportions of "long" responses as a function of Relevant magnitude, Irrelevant magnitude, and Task (Spatial task in the left part; temporal task in the right part) separately for the non-demanding condition (Experiment 1, upper part) and the demanding condition (Experiment 2, lower part)

depending on the task) and Irrelevant magnitude (the two levels of distance or duration, depending on the task) manipulated within participants. This analysis revealed a significant main effect of Task ($F(1, 15) = 5.67$, $p = .031$, $\eta^2 p = .27$). Participants were significantly faster to judge spatial distances than temporal intervals (see Fig. 4). This analysis also revealed significant effects of Relevant magnitude and Irrelevant magnitude (both Fs > 13.70, and ps < .001), and significant interactions between Task and Relevant magnitude, and between Relevant magnitude and Irrelevant magnitude (both Fs > 4.21, and ps < .05).

Conclusion of Experiment 1

As expected, spatial irrelevant information modulated temporal judgments to a larger extent than the reverse. This finding confirms the advantage of space over time. However, the analyses on WRs and RTs provide evidence for a substantial mismatch in terms of perceptual sensitivity and cognitive demands between the temporal and spatial tasks. The WRs revealed that perceptual sensitivity was higher in the spatial task; while the RTs suggested that cognitive demands were clearly lower in this task compared to the temporal task.

Table 1 The mean point of subjective equality (PSE), Weber ratios (WRs), and standardized PSE as a function of the Experiment ("non-demanding Experiment" referring to Experiment 1 vs. "demanding Experiment" referring to Experiment 2), the Task and the Irrelevant magnitude. WRs represent the ratio of the just-noticeable variation to the initial stimuli intensity. Note that WRs are expressed for all the spatial distances in the spatial task; and all the temporal intervals in the temporal task

Experiment	Task	n	Irrelevant magnitude	PSE		WR		Standardized PSE	
				Mean	(SE)	Mean	(SE)	Mean	(SE)
Non-demanding	Spatial Task	(n = 16)	100ms	67	(3.10)	0.17	(0.074)	0.205	(0.27)
			600ms	63	(2.74)	0.16	(0.063)	-0.205	(0.24)
	Temporal Task	(n = 16)	1.6°	471	(21.72)	0.14	(0.021)	0.485	(0.23)
			12.8°	378	(21.66)	0.31	(0.041)	-0.485	(0.23)
Demanding	Spatial Task	(n = 32)	100ms	41	(2.47)	0.05	(0.053)	0.564	(0.19)
			600ms	38	(2.32)	0.06	(0.045)	-0.564	(0.19)
	Temporal Task	(n = 32)	3.2°	389	(16.10)	0.15	(0.016)	0.308	(0.16)
			4.8°	355	(15.90)	0.18	(0.028)	-0.308	(0.17)

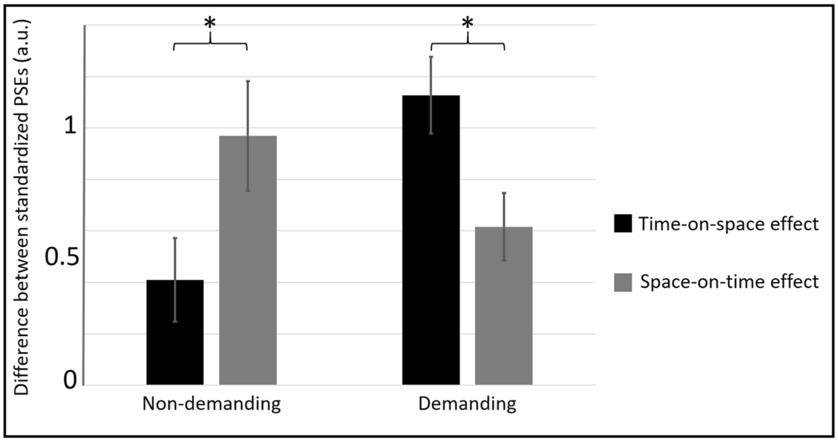

Fig. 3 The difference of standardized point of subjective equality (PSE) values between Irrelevant magnitudes ("Standardized PSE value for Irrelevant 1" - "Standardized PSE value for Irrelevant 5"), representing the strength of interference effects as a function of the Task separately for the non-demanding and demanding experiments, Experiments 1 and 2, respectively

Experiment 2: Demanding spatial task

The aim of Experiment 2 was to enhance cognitive demands in the spatial task to further explore spatiotemporal interactions. The spatial task difficulty was greatly increased by manipulating distances (see *Procedure* for a detailed description and Fig. 1), while temporal intervals remained unchanged. Il should be noted that a number of studies have already attempted to equate difficulty in spatial and temporal tasks, but the authors usually opted to lower difficulty in the temporal task (Coull et al., 2015, but see Homma & Ashida, 2019, in the *General discussion*). Increasing difficulty in the spatial task by reducing the gap between distances aimed to break processing automaticity of spatial information (Dormal & Pesenti, 2013); hence, the time required to efficiently process spatial distances should increase. Our objective was to test the strength of time-on-space interference in the context of a demanding spatial task.

Methods

Participants

A total of 36 participants (including 18 women; 32 right-handed) between 18 and 42 years of age (mean 21.97, SD 4.98) participated in this study. Sample size was determined using effect sizes from previous research examining space-time interference (Starr & Brannon, 2016; effect size $f = .80$, with power ($1 - ß$ err prob) = .95, and $\alpha = .05$), for a main experimental design that has two within-subjects factors and one between-subjects factor (G*Power, Faul et al., 2007). All the participants, who were recruited from the Université Paul Valéry Montpellier (France), gave their written informed consent. The study was carried out according to the principles of the Declaration of Helsinki and in accordance with the Department of Psychology Ethics Committee guidelines

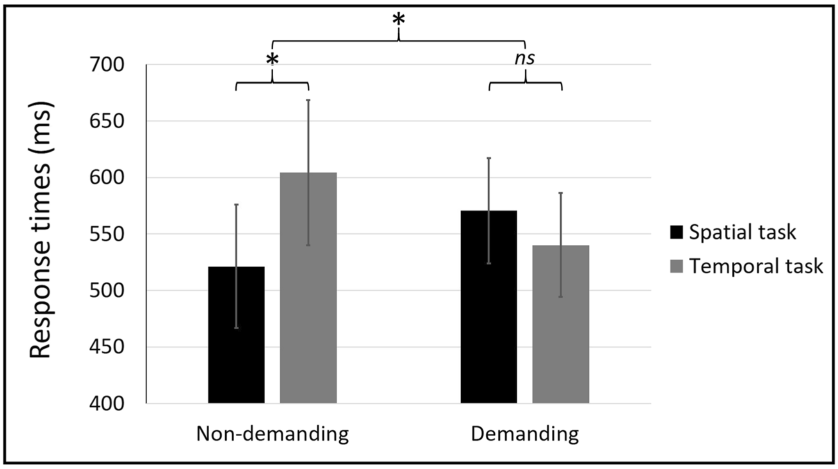

Fig. 4 The response times as a function of the Task (Spatial vs. Temporal) separately for the non-demanding and demanding experiments (Experiment 1 and 2, respectively)

(Université Paul Valéry Montpellier). All reported to have normal or corrected-to-normal vision.

Apparatus

A PC (Acer Aspire 5742) running E-Prime 2.0 software (Schneider et al., 2002) controlled stimulus presentation, timing operations and data collection, as in Experiment 1.

Stimuli and procedure

Stimuli and procedure were identical to those of Experiment 1, except that a 0.4° gap was set between two consecutive distances, so that the shorter distance covered 3.2° and the longer 4.8° (3.2°, 3.6°, 4.0°, 4.4°, and 4.8°; see Fig. 1, Panel B). Furthermore, in the temporal task, the two irrelevant distance anchors used to produce space-on-time interference were of 3.2° and 4.8° for the shorter and the longer distances, respectively.

Results

The data from four participants were removed from statistical analyses due to extremely low performance on the anchors (shorter and longer durations or distances). The final sample included 32 participants. Statistical analyses similar to those of Experiment 1 were conducted. To test perceptual sensitivity, we performed a repeated-measures ANOVA on WRs with the variables Task (Spatial, Temporal) and Irrelevant magnitude (the two levels of distance or duration, depending on the task) manipulated within participants. It showed main effects of Irrelevant magnitude and of Task ($F(1, 31) = 6.35, p = .017, \eta^2 p = .17$ and $F(1, 31) = 90.40, P < .001, \eta^2 p = .75$, respectively), but no significant Task × Irrelevant magnitude interaction ($F(1, 31) = 2.80, p>.05, \eta^2 p = .08$). These results show lower WRs in the spatial task, thus indicating that spatial judgments were more precise than temporal ones (see Table 1). Importantly, reducing the gap between distances did not entail a decline in perceptual sensitivity in the spatial task.

To further analyze interference effects, we performed a repeated-measures ANOVA on standardized PSE value, with the variables Task (Spatial, Temporal) and Irrelevant magnitude (the two levels of distance or duration, depending on the task) manipulated within participants. As PSE were standardized per condition and task, we only report the main effect or interaction related to Irrelevant Magnitude. The results show a main effect of Irrelevant magnitude ($F(1, 31) = 59.20, p < .001, \eta^2 p = .66$) and, as predicted, a significant interaction effect of Irrelevant magnitude × Task ($F(1, 31) = 9.56, p = .004, \eta^2 p = .24$), revealing that the time-on-space effect is higher than the space-on-time effect (see Fig. 3).

Finally, we performed a repeated-measures ANOVA on mean RTs with the variables Task (Spatial, Temporal), Relevant magnitude (the five levels of distance or duration, depending on the task) and Irrelevant magnitude (the two levels of distance or duration, depending on the task) manipulated within participants. This analysis revealed a main effect of Relevant magnitude ($F(4, 124) = 23.91, P < .001, \eta^2 p = .44$) and significant Task × Relevant magnitude as well as Relevant magnitude × Irrelevant magnitude interactions (both Fs > 4.66, and ps < .05). But more importantly, we found no significant effect of Task ($F(1, 31) = 1.23, p = .276, \eta^2 p = .038$), thus suggesting that mean RTs were similar to judge spatial distances and temporal intervals (see Fig. 4).

Conclusion of Experiment 2

The results of Experiment 2 show that increasing difficulty in the spatial task slowed down the decision process. Participants required the same amount of time to judge a spatial distance or a temporal interval, suggesting that cognitive demands were balanced for the spatial and temporal tasks, in contrast with Experiment 1. More importantly, Experiment 2 provides evidence for a massive time-on-space effect, larger than the space-on-time effect. Spatial judgments were indeed biased by irrelevant temporal information to a larger extent than were temporal judgments by irrelevant spatial information. To our knowledge, this is the first piece of evidence for a superiority of time over space in the visual modality. It is noteworthy that spatio-temporal interference might not directly depend on perceptual sensitivity as (i) WRs were lower for the spatial than temporal task in Experiment 2 (as in Experiment 1); and (ii) WRs appears to be lower in Experiment 2 as compared to Experiment 1. To statistically investigate this issue, we conducted a comparison of Experiments 1 and 2.

Comparison of Experiments 1 and 2

In order to directly compare Experiment 1 and 2, we conducted three ANOVAs including the 48 participants, with the variable Experiment (non-demanding Experiment referring to Experiment 1 vs. demanding Experiment referring to Experiment 2) manipulated between participants, the variables Task (Spatial, Temporal) and Irrelevant magnitude (the two levels of distance or duration, depending on the task) manipulated within participants.

A repeated-measures ANOVA on WRs revealed significant main effects of Task, of Experiment and of Irrelevant magnitude, as well as significant interactions between Task and Irrelevant magnitude; between Irrelevant magnitude and Experiment and a significant interaction effect of Task × Irrelevant magnitude × Experiment (all Fs > 10.27, and ps < .011), but no significant effect of Task × Experiment ($F(1, 46)$

= 1.48, p = .230, η^2p = .03). The interaction Task × Irrelevant magnitude × Experiment was further explored conducting post hoc analyses. The analyses mainly revealed that spatial WRs were significantly lower in the demanding task compared to the non-demanding (p = .025), but this difference did not survive Bonferroni correction (p = .15). Regarding temporal WRs, no significant difference was observed between the two experiments for the short irrelevant magnitude while they significantly improved in the demanding task for the long irrelevant magnitude (p = .03).

For the repeated-measures ANOVA on standardized PSE value, the results showed a main effect of the Irrelevant magnitude (F(1, 46) = 65.34, P < .001, η^2p = .58), and no significant Irrelevant magnitude × Experiment interaction (F(1, 46) = 0.88, p = .35, η^2p = .02) neither significant Irrelevant magnitude × Task interaction (F(1, 46) = 0.03, p = .87, η^2p = .001), but as predicted, the Experiment × Task × Irrelevant interaction was highly significant (F(1, 46) = 14.42, p < .001, η^2p = .24). Planned comparisons were then conducted to directly test our hypotheses. The planned comparisons conducted in the non-demanding and demanding experiments for both tasks revealed significant Space-on-time and Time-on-space effects in the non-demanding Experiment (F(1, 46) = 24.67, p < .001 and F(1, 46) = 4.40, p = .04, respectively; see Fig. 4). In the demanding Experiment, the space-on-time and time-on-space effects were also highly significant (F(1, 46) = 19.90, p < .001 and F(1, 46) = 66.58, p < .001, respectively; see Fig. 4). Finally, to examine the flexibility of the space-on-time and time-on-space effects, Bonferroni post hoc tests revealed that the time-on-space effect was larger in the demanding than in the non-demanding Experiment (p = .02); and, more importantly, an additional post-hoc confirmed that the time-on-space effect was larger than the space-on-time effect in the demanding Experiment (p = .02).

Finally, the repeated-measures ANOVA on mean RTs revealed significant main effects of Relevant magnitude and of Irrelevant magnitude (both Fs > 15.69, and ps < .001), and significant interactions (all Fs > 2.59, and ps < .05). Importantly, the interaction between Task and Experiment reached significance (F(1, 46) = 6.06, p = .018, η^2p = .116) revealing that the gap between the spatial and temporal tasks was overcome in Experiment 2 (see Fig. 4).

Overall, these analyses suggest that while participants were able to precisely judge spatial distances and temporal intervals, performance was clearly influenced by irrelevant magnitude (time and space, respectively). In Experiment 1, we replicated the classical pattern of magnitude interferences, with a sharp advantage of space over time. But this pattern reversed in Experiment 2 when the spatial task became demanding. Time did modulate spatial estimates, and to a larger extent than did space on time. The size of spatiotemporal interference appears to depend on the cognitive resources engaged in the spatial task. Critically, time-on-space interference was much larger when the decision process was slow (long RTs), but it was not associated with low perceptual discriminability. The time-on-space effect was increased in Experiment 2 where the WRs were very low, revealing precise spatial estimates. This finding is consistent with a study conducted in the tactile modality by Kuroda and Grondin (2013), in which spatiotemporal interference was independent of the Weber fractions. Overall, Experiments 1 and 2 provide evidence for a massive effect of time over space when cognitive demands in the spatial task are high, indexed by the slowdown of the decision process rather than by perceptual sensitivity.

Experiment 3

In the following experiment, the gap between distances varied in a within-participant design to directly test the flexibility of time-on-space interference (instead of the between-participant design used in Experiments 1 and 2). Participants performed a demanding and a non-demanding spatial block (or the other way around given that block order was counterbalanced across participants). To assess time-on-space interference,[3] PSEs were analyzed; and to figure the resources engaged in the task, we also analyzed WRs and RTs. Our objective was to provide evidence that for a given participant, time-on-space interference could be flexible and depends on the resources engaged in the spatial task.

Methods

Participants

A total of 20 participants (including 13 women; 16 right-handed) between 17 and 39 years of age (mean 25.50, SD 4.78) participated in this study. All the participants, who were recruited from the Université Paul Valéry Montpellier (France), gave their written informed consent. The study was carried out according to the principles of the Declaration of Helsinki and in accordance with the Department of Psychology Ethics Committee guidelines (Université Paul Valéry Montpellier). All reported to have normal or corrected-to-normal vision.

Apparatus

A PC (Acer Aspire 5742) running E-Prime 2.0 software (Schneider et al., 2002) controlled stimulus presentation, timing operations and data collection. Stimuli were presented on the computer 15.6-in. screen, 1,366 × 768 pixels (60 Hz). Manual responses were collected by clicking on the left and right buttons of the touchpad with the participants' right hand.

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[3] Participants only performed spatial judgments in Experiment 3.

Stimuli and procedure

Stimuli were identical to those used in Experiments 1 and 2. The procedure was also highly similar, except that participant only performed spatial judgments. Distances varied across blocks, corresponding to the non-demanding condition (Experiment 1) or to the demanding condition (Experiment 2). To resemble as much as possible Experiments 1 and 2, participants were told that the experiment consisted of a series of spatial and temporal blocks presented in mixed order. Participants were informed that reference durations and distances (the shorter and longer ones) may change across blocks. Each spatial block was preceded by the related instructions and training.

Results

As preliminary analyses show no significant Condition effect but a tremendous Block order effect, this factor was included in the statistical analyses.

We performed a repeated-measures ANOVA on WRs, with the factor Block order (Ascending demand and Descending demand) manipulated between participants, and the variables Condition (Non-demanding vs. Demanding) and Irrelevant magnitude (100 ms and 600 ms) manipulated within participants. Importantly, this analysis revealed neither a significant effect of Condition nor a significant Condition × Block order interaction (both *F*s(1, 18) < 1). The effect of Irrelevant magnitude reached significance (*F*(1, 18) = 4.93, *p* = .039, $\eta^2 p$ = .22), confirming that WRs are lower for the short duration Table 2.

To analyze time-on-space interference, we performed a repeated-measures ANOVA on standardized PSE values (see the *Data analysis* section of Experiment 1 for further details on the procedure), with the factor Block order (Ascending demand and Descending demand) manipulated between participants, and the variables Condition (non-demanding and demanding) and Irrelevant magnitude (100 ms and 600 ms) manipulated within participants. The results showed a main effect of Irrelevant magnitude (*F*(1, 18) = 10.87, *p* = 004, $\eta^2 p$ = .38), but no significant Irrelevant magnitude × Condition interaction (*F*(1, 18) = 2.35, *p* = .143, $\eta^2 p$ = .12). However, the Irrelevant magnitude × Condition × Block order interaction was significant (*F*(1, 18) = 8.11, *p* = .011, $\eta^2 p$ = .31), suggesting that time-on-space interference depends on Condition and Block order. Separate ANOVAs revealed no significant effect or interaction (all *F*s < 2.66, and *p*s > .05) for the ascending order, but revealed a significant effect of Irrelevant magnitude (*F*(1, 9) = 8.67, *p* = .016, $\eta^2 p$ = .49), as well as a Condition × Irrelevant magnitude interaction (*F*(1, 9) = 7.06, *p* = .026, $\eta^2 p$ = .44) for descending order. Overall, these results suggest that time-on-space interference was much larger in the demanding condition, *if and only if* participants started with the demanding block (see Fig. 5).

Finally, we performed a repeated-measures ANOVA on RTs, with the factor Block order manipulated between participants, and the variables Condition (non-demanding vs. demanding), Relevant magnitude (the five levels of distance, depending on the condition) and Irrelevant magnitude (100 ms and 600 ms) manipulated within participants. This analysis showed a main effect of Condition (*F*(1, 18) = 4.63, *p* = .045, $\eta^2 p$ = .21) and a significant Condition × Block order interaction (*F*(1, 18) = 6.86, *p* = .017, $\eta^2 p$ = .28), suggesting that RTs depend on Block order. It also revealed a main effect of Relevant magnitude (*F*(4, 72) = 30.30, *P* < .001, $\eta^2 p$ = .63) and a significant interaction between Condition and Relevant magnitude (*F*(4, 72) = 3.95, *p* = .006, $\eta^2 p$ = .18).

We thus conducted separate ANOVAs for each block. For the ascending order, the results revealed a main effect of Relevant magnitude (*F*(4, 36) = 13.79, *P* < .001, $\eta^2 p$ = .63) and a significant interaction Condition × Relevant magnitude

Table 2 Mean point of subjective equality (PSE), Weber ratios (WRs), and standardized PSE as a function of Block order, Condition, and Irrelevant magnitude

Bloc order	Condition	*n*	Irrelevant magnitude	PSE		WR		Standardized PSE	
				Mean	(SE)	Mean	(SE)	Mean	(SE)
Ascending order	Non demanding	(*n* = 10)	100ms	72	(5.29)	0.07	(0.032)	0.437	(0.35)
			600ms	66	(3.20)	0.11	(0.023)	0.035	(0.21)
	Demanding	(*n* = 10)	100ms	40	(1.00)	0.07	(0.004)	0.204	(0.39)
			600ms	39	(0.77)	0.07	(0.009)	0	(0.30)
Demanding	Non-demanding	(*n* = 10)	100ms	64	(4.26)	0.05	(0.019)	-0.082	(0.28)
			600ms	60	(5.67)	0.09	(0.037)	-0.390	(0.38)
	Demanding	(*n* = 10)	100ms	40	(0.59)	0.06	(0.011)	0.382	(0.23)
			600ms	38	(0.75)	0.07	(0.010)	-0.586	(0.29)

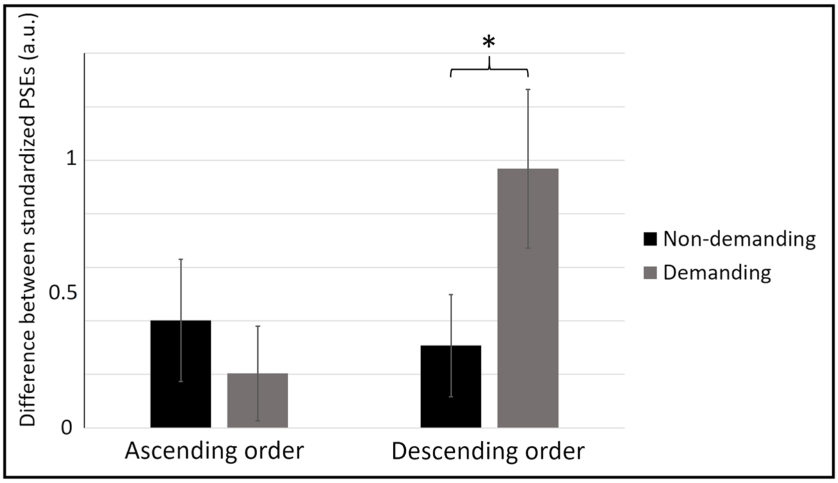

Fig. 5 The difference in standardized point of subjective equality (PSE) values between Irrelevant magnitudes ("Standardized PSE value for Irrelevant 1" – "Standardized PSE value for Irrelevant 5"), representing the size of time-on-space interference as a function of Condition (non-demanding - demanding) separately for "Block order 1" (non-demanding condition, then demanding condition) and "Block order 2" (demanding condition, then non-demanding condition)

($F(4, 36) = 3.67$, $p = .013$, $\eta^2 p = .29$), but no significant effect of Condition ($F(1, 9)<1$). For the descending order, the analysis revealed a main effect of Relevant magnitude ($F(4, 36) = 18.62$, $P < .001$, $\eta^2 p = .67$) but, more importantly, a main effect of Condition ($F(1, 9) = 9.72$, $p = .012$, $\eta^2 p = .52$). The results indicated that RTs are similar in the two conditions when participants first completed the non-demanding condition, but significantly differ when participants started with the demanding condition. The decision process for spatial judgments was much slower in the demanding condition when this block was delivered first (see Fig. 6).

Conclusion of Experiment 3

Experiment 3 mainly replicates the findings of Experiment 2 in a within-subject design. Time-on-space interference turned out to be flexible. Participants performed a *spatial task* with highly discriminable distances (non-demanding condition) and scarcely discriminate distances (demanding condition) depending on the block. As block order was counterbalanced across subject, difficulty was either descending or ascending. In the ascending order, distance discriminability did not significantly influence the strength of the time-on-space effect across the non-demanding and demanding conditions. We hypothesized that the non-demanding block served as an extensive training which, in turn, prevented the emergence of a massive time-on-space effect. In line with this assumption, in the ascending order, RTs were not significantly longer in the demanding block. In sharp contrast, participants who performed the descending order, showed a large and reliable time-on-space effect in the demanding block, associated with longer RTs. Overall, this experiment illustrates

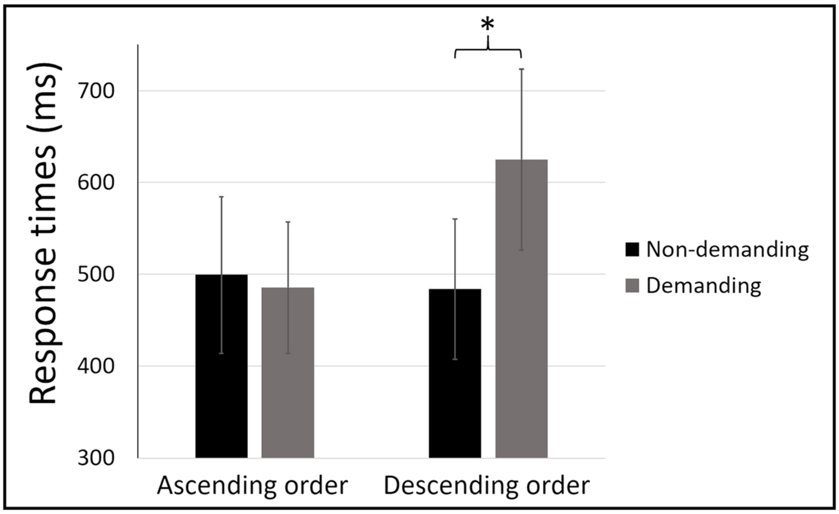

Fig. 6 The response times as a function of the Condition separately for the "non-demanding, then demanding" and the "demanding condition, then non-demanding" groups

the flexibility of time-on-space interference. When individuals performed a demanding spatial task, their perceptual judgments were biased by irrelevant temporal information. As revealed by the pattern of space-time interferences as a function of block order, time-on-space interference is clearly linked to the cognitive resources engaged in the spatial task, rather than to perceptual sensitivity per se.

General discussion

In the present study, we aimed to investigate spatiotemporal interactions. We hypothesized that the low requirements in the spatial task led to the advantage of space over time repeatedly observed in the literature. Experiment 1 replicated this advantage and suggested, based on WRs and RTs, that the spatial task was not as demanding as the temporal one. In Experiment 2, the gap between distances was reduced for the purpose of driving participants to engage more resources in the spatial task, without adversely affecting perceptual sensitivity. Spatial WRs were indeed excellent but RTs much longer, suggesting that the automaticity of spatial processing was hindered. Interestingly, in this context, time did modulate spatial estimates, and to a larger extent than space did on time (time-on-space>space-on-time – see also Experiment 3). Spatiotemporal interferences seem thus to depend on cognitive resources, at least in the context of magnitude processing. The labels Space and Time embrace a large series of cognitive abilities. Space can indeed refer to navigation, localization, size estimation or perceived distance. In the same vein, the label Time can be interchangeably used to encompass timing abilities with short and long durations (from hundreds of milliseconds to hours, or even days), and also temporal knowledge associated to temporal order or to past, present and future events. It would be overstating the case to posit, on the basis of the present study, that any type of spatial processing is biased by temporal information when sequentially delivered. There is clear evidence in the literature that spatial and temporal information processing are dissociated (see Candini et al., 2022; Ekstrom et al., 2011; Isham et al., 2018). Nonetheless, our results have implications for the theoretical models of magnitude processing.

To match the cognitive demands in the context of temporal and spatial processing, it might be essential to disrupt the automaticity of spatial judgments by (i) decreasing saliency of spatial information and by (ii) using sequential sensory information for spatial judgments. Time processing – in contrast with other quantities such as space or number – inherently relies on sequential or cumulative information that may be processed at a neural level by ramping activity neurons as well as time-tuned neurons (see Tsouli et al., 2022). Working memory is inevitably involved in timing to process incremental sensory information over time (Coull et al., 2015; Coull & Droit-Volet, 2018). Yet, spatial or numerical information can either be delivered simultaneously or sequentially by using dynamic displays (such as a growing line for instance). Balancing the need of working memory across dimensions has proven to be decisive when investigating commonalities between time, space and even number (see Droit-Volet, 2010; Droit-Volet et al., 2008). An essential criterion to maximize time-on-space interference in the context of magnitude processing might thus be to deliver spatial information sequentially (see Droit-Volet, 2010; Droit-Volet et al., 2008).

Overall, it might be necessary for the time-on-space effect to occur to disrupt the automaticity of spatial processing, fostered by the visual modality. Cai and Connell (2015) stressed the role of perceptual acuity and modality-specific processing on space-time interferences (for a review, see Loeffler et al., 2018). Using the haptic modality, they demonstrated that irrelevant temporal information could markedly bias spatial judgments and argued that the ability to represent spatial and temporal magnitude depends on the sensory modality. The perceptual acuity issue has also been addressed in the literature using the visual modality (Homma & Ashida, 2015; also see DeWind et al., 2015; Ernst & Banks, 2002). Homma and Ashida (2015) claimed that the saliency of spatial information is responsible for the superiority of the Space-on-time effect. By manipulating the saliency and difficulty of both tasks, they pointed up the flexibility of spatiotemporal interferences. However, space consistently affected time more than the reverse (but see Homma & Ashida, 2019[4]). In our opinion, Homma and Ashida (2015, 2019) hardly highlighted asymmetric effects of time on space because the spatial task was perceptually very demanding but did not involve sequential sensory information – they used static lines of different lengths.

While further research is needed to outline the specific criteria leading to a massive time-on-space effect, the current results clearly question the relevance of the Conceptual Metaphor Theory (Boroditsky, 2000; Casasanto & Boroditsky, 2008; Lakoff & Johnson, 1980, 1999;). Similar evidence for unbalanced or unidirectional influence of time on space in the haptic or auditory modalities (Cai & Connell, 2015) already undermined the Conceptual metaphor theory. The flexibility of spatiotemporal interactions highlighted here, in the visual modality, definitely rules out this theoretical account.

In parallel, spatiotemporal interference have been accounted for by theoretical models based on imputed velocity. Given that from daily experience, observers have expectancies about

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[4] In this study, the requirements imposed on the spatial task were so high that unfortunately, participants apparently performed near chance level. In this context, one can argue that individuals had no alternative but to rely on temporal information (albeit irrelevant). In sharp contrast, in our study, participants were able to accurately judge relevant magnitude in both the spatial and temporal tasks.

moving objects, two objects, albeit spatially and temporarily separated, are often perceived as a single moving object (apparent motion; Collyer, 1977; Jones & Huang, 1982). Space-time interferences (Kappa and Tau effects) are usually adequately explained by imputed velocity, but this interpretation does not hold for our results. The imputed velocity hypothesis predicts larger time-on-space effects for larger absolute distances and yet we observed here the opposite result here. In the demanding condition (Exps. 2 and 3), as spatial distances were physically shorter than those used in the non-demanding condition (Exps. 1 and 3), apparent velocity should decrease and result in a decline of the time-on-space effect (Henry & McAuley, 2009; Henry et al., 2009; Reali et al., 2019; also see Goldreich, 2007, for other "speed-based" interpretation). Yet, in sharp contrast with such a prediction, time-on-space effect was significantly larger in the demanding condition.

A couple of very recent studies looked further into the issue of magnitude interferences and suggest that space-time interactions occur at a memory stage (Cai et al., 2018; also see Wang & Cai, 2022). In a series of experiments, participants were asked to simultaneously process spatial and temporal information conveyed by visual stimuli, and then to make judgments on either temporal, spatial or both information. Their results clearly demonstrate that space is prone to temporal interference as a result of memory interference. They propose a Bayesian model whereby memory noise plays a critical role in the susceptibility to interferences (also see Wang & Cai, 2022). Recent studies in the field have also put forward the role of working memory in space-time interference (Cai & Connell, 2016; Starr & Brannon, 2016; also see Cai & Wang, 2014). For instance, Starr and Brannon (2016) demonstrated that space did influence temporal estimates but only when some resources in visuospatial working memory were available. Overall, it suggests that the automatic processing of spatial information shapes the spatiotemporal interferences (space-on-time and time-on-space) that might arise in working memory.

Finally, the spatiotemporal interference observed in this study could also be supported by a spatial representation account or a generalized magnitude account according to which time-space interference emerges from a shared representation format for these two dimensions or could be magnitude-based, as suggested by AToM (Bueti & Walsh, 2009; Walsh, 2003). This interpretation fits well with studies in time-numerosity interference in which temporal information drastically interfered with magnitude judgments (numerical; see Lambrechts et al., 2013; Martin et al., 2017; Tsouli et al., 2019). This interpretation is also consistent with the study of Cohen-Kadosh et al. (2008) in which they pointed out that when the relevant and irrelevant dimensions are difficult to discriminate (low discriminability/high cognitive load), the magnitude interference might occur during the comparison stage. As the specific brain regions dedicated to processing relevant magnitude are exceeded, other areas common to various magnitudes might be involved to compensate.

However, given that space-time interactions are highly flexible, being either uni- or bi-directional, either symmetrical or asymmetrical, as a function of sensory modality acuity and of the gradient of automaticity (see Loeffler et al., 2018), it is hard to rely on this behavioral signature to support the hypothesis of a generalized magnitude system. Spatiotemporal interactions could emerge at different processing stages (see Hayashi et al., 2013, for time-numerosity interaction). Having now robust evidence that time can drastically influence spatial estimates, further research will determine at what stage(s) space-time interactions occur and what the cerebral regions involved in time-on-space interference are. Additionally, although the overarching objective was to investigate the unbalanced interaction between space and time, one could wonder to what extent spatial processing is susceptible to other types of interference. However, ample evidence suggests that space can be biased by other types of information. Space processing is biased by numerosity (e.g., de Hevia et al., 2014; Dormal et al., 2018). Magnitude judgement can be influenced by emotional contents. Experimental evidence has been repeatedly reported in timing research, and, more recently, in space and number processing (see, e.g., Droit-Volet, 2010; Hamamouche et al., 2017; Young & Cordes, 2013). Further investigation is needed to determine the dimensions that affect spatial processing and to determine at what stage(s) they occur.

Open practices statement None of the studies reported in this article were preregistered. The data have not been made available on a permanent third-party archive. However, requests for the data can be sent to the corresponding author. The data will then be open and available.

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