



# Space–time interdependence: Evidence against asymmetric mapping between time and space



Zhenguang G. Cai <sup>a,b,d,\*</sup>, Louise Connell <sup>c,d,\*</sup>

<sup>a</sup> Department of Experimental Psychology, University College London, United Kingdom

<sup>b</sup> School of Psychology, University of Plymouth, United Kingdom

<sup>c</sup> Department of Psychology, Lancaster University, United Kingdom

<sup>d</sup> School of Psychological Sciences, University of Manchester, United Kingdom

## ARTICLE INFO

### Article history:

Received 20 August 2012

Revised 3 November 2014

Accepted 22 November 2014

Available online 13 December 2014

### Keywords:

Time

Space

Representation

Haptic perception

Visual perception

Metaphor

## ABSTRACT

Time and space are intimately related, but what is the real nature of this relationship? Is time mapped metaphorically onto space such that effects are always asymmetric (i.e., space affects time more than time affects space)? Or do the two domains share a common representational format and have the ability to influence each other in a flexible manner (i.e., time can sometimes affect space more than vice versa)? In three experiments, we examined whether spatial representations from haptic perception, a modality of relatively low spatial acuity, would lead the effect of time on space to be substantially stronger than the effect of space on time. Participants touched (but could not see) physical sticks while listening to an auditory note, and then reproduced either the length of the stick or the duration of the note. Judgements of length were affected by concurrent stimulus duration, but not vice versa. When participants were allowed to see as well as touch the sticks, however, the higher acuity of visuohaptic perception caused the effects to converge so length and duration influenced each other to a similar extent. These findings run counter to the spatial metaphor account of time, and rather support the spatial representation account in which time and space share a common representational format and the directionality of space–time interaction depends on the perceptual acuity of the modality used to perceive space.

© 2014 Elsevier B.V. All rights reserved.

## 1. Introduction

Though our immediate perception of the world is limited to our senses such as vision and hearing, we can build on these senses to develop other knowledge domains such as *space*. How we perceive and represent more abstract

domains such as *time*, however, has been a perennial philosophical question. Many researchers have suggested that abstract domains are grounded to some extent in more familiar concrete domains that we develop through sensorimotor experience (e.g., Barsalou & Wiemer-Hastings, 2005; Clark, 1973; Gibbs, 1994; Lakoff & Johnson, 1980, 1999). Time, for example, can be understood through the domain of space, as reflected in our use of language. Speakers of English often talk about time in spatial terms (e.g., *a long/short time*) and sometimes space in temporal terms (e.g., *I am five minutes from the airport*). A range of studies have provided evidence that these linguistic expressions reflect a deeper conceptual bridge between time and space. For example, space affects the perception of temporal

\* Corresponding authors. Address: Zhenguang G. Cai, Department of Experimental Psychology, Division of Psychology and Language Sciences, University College London, 26 Bedford Way, London WC1H 0AP, UK (Z.G. Cai), Louise Connell, Department of Psychology, Fylde College, Lancaster University, Bailrigg, Lancaster LA1 4YF, UK (L. Connell).

E-mail addresses: [zhenguangcai@gmail.com](mailto:zhenguangcai@gmail.com) (Z.G. Cai), [l.connell@lancaster.ac.uk](mailto:l.connell@lancaster.ac.uk) (L. Connell).

durations such that people experience longer subjective time when they imagine themselves inside a larger scale model of a room than inside a smaller one (DeLong, 1981), or when they see a larger square than a smaller one (Xuan, Zhang, He, & Chen, 2007), a longer sweeping gesture than a shorter one (Cai, Connell, & Holler, 2013), or a longer line than a shorter one (Casasanto & Boroditsky, 2008).

There are two alternative accounts of the relationship between time and space representations. According to the *spatial metaphor* account, people employ spatial metaphors in thinking or talking about time such that they use their concrete spatial experience to support their understanding of abstract time processing (Boroditsky, 2000; Clark, 1973; Gibbs, 2006; Lakoff & Johnson, 1980, 1999). The temporal relation of two events can be expressed metaphorically as a relation between two locations in space (e.g., tomorrow is ahead of yesterday). Similarly, a temporal duration can be metaphorically envisioned as the distance from a spatial location representing the onset of the duration and a spatial location representing the offset of the duration. Critically, the spatial metaphor account assumes that time and space remain two separate representational systems with an asymmetric mapping between them: concurrent spatial information should always affect its dependent domain of time to a greater extent than concurrent temporal information can affect space (Casasanto & Boroditsky, 2008; Casasanto, Fotakopoulou, & Boroditsky, 2010; Merritt, Casasanto, & Brannon, 2010). In other words, the asymmetry of space–time interaction manifests itself as one of the following two possibilities: either space unilaterally affects time; or space and time affect each other but the effect of space on time should be greater than that of time on space. The account rules out the possibility that time affects space but is not itself affected by space.

Alternatively, according to the *spatial representation* account of time–space relations, temporal and spatial information are processed in a common neural substrate and share representational and attentional resources. Such a position has received support from behavioural demonstrations of spatial interference on time perception (Frassinetti, Magnani, & Oliveri, 2009; Xuan et al., 2007), imaging findings of common neural substrates subserving space and time processing (Assmus, Marshall, Noth, Zilles, & Fink, 2005; Assmus et al., 2003; Oliveri, Koch, & Caltagirone, 2009; Parkinson, Liu, & Wheatley, 2014), and neuropsychological observations of distorted time perception in space-neglect patients (Basso, Nichelli, Frassinetti, & di Pellegrino, 1996; Danckert et al., 2007). According to the account, time is closely related to space in action and perception: space and time are often coordinated in action and correspond to each other in movement (e.g., things travel a certain distance in a certain time; Gallistel & Gelman, 2000; Srinivasan & Carey, 2010). Thus, temporal duration and spatial distance may share a representational format, such that two events are separated by a particular duration in the same way that two locations are separated by a particular distance. Some stronger versions of spatial representation theories have argued that time, space and number all share a common magnitude representation

(Buetti & Walsh, 2009; Burr, Ross, Binda, & Morrone, 2010; Gallistel & Gelman, 2000; Lambrechts, Walsh, & van Wassenhove, 2013; Walsh, 2003), but a weaker version of the spatial representation account of time does not necessarily require the magnitude assumption, and hence can also accommodate the spatial representation of non-magnitude information such as acoustic pitch (Connell, Cai, & Holler, 2013). Critically, according to the spatial representation account, rather than comprising separate representational domains, time and space occupy an overlapping temporo-spatial representation that may be affected by concurrent temporal or spatial information. Since the same representation can subserve both temporal and spatial processing, the spatial representation account thus differs from the spatial metaphor account in allowing both directions of space–time interaction; importantly, in direct contrast with the spatial metaphor account, it allows time to unilaterally affect space in certain circumstances (as we describe below).

Empirical evidence has thus far favoured the spatial metaphor account, with the strongest evidence coming from studies showing apparently robust asymmetric effects of space on time in nonlinguistic paradigms. For example, Casasanto and Boroditsky (2008; see also Casasanto et al., 2010) showed participants a horizontal line onscreen, which varied in its length (200–800 pixels in steps of 75 pixels) and its presentation duration (1000–5000 ms in steps of 50 ms). After the disappearance of the line, participants were cued to reproduce either its length or duration. Length reproduction involved using the mouse to click first on an X symbol on the left of the screen, then moving the mouse rightwards and clicking again to demarcate a particular length. Duration reproduction involved clicking first on an hour-glass symbol to start a particular duration and then clicking again to end it. They found that people's estimates of the line's duration increased as a function of its length, but that estimates of length remained unaffected by the duration of the line onscreen. Several variants of the task produced the same effects, regardless of whether duration was presented as an auditory tone as well as the visual line onscreen, or whether the line grew onscreen to its final length or remained fixed. A later study using a different paradigm, where participants categorised the length or duration of a line as long or short according to learned standards, did find an effect of time on space (Merritt et al., 2010; see also Srinivasan & Carey, 2010), but since this effect was smaller than that of space on time, the asymmetric hypothesis of the spatial metaphor account was supported.

The above studies all use the visual modality to present spatial information. However, spatial representations are not themselves visual, and rather are handled by a multimodal or supramodal system that draws perceptual input from visual, haptic, or auditory modalities (or even from linguistic descriptions) in order to create a common spatial representation (Bryant, 1992; Giudice, Betty, & Loomis, 2011; Lacey, Campbell, & Sathian, 2007; Renier et al., 2009; Struiksma, Noordzijk, & Postma, 2009). In some cases, visual and haptic perceptions give rise to comparable representations. For example, people use the same mecha-

nism (i.e., mental scanning) when they are searching spatial memories formed via visual or haptic modalities (e.g., Kosslyn, Ball, & Reiser, 1978; Röder & Rösler, 1998), and spatial layout or route learning can be equally accurate when perceived through vision or touch (Giudice, Klatzky, & Loomis, 2009; Giudice et al., 2011). More usually, though, visual perception leads to better spatial performance than haptic perception alone (e.g., Cattaneo & Vecchi, 2008; Ernst & Banks, 2002; Helbig & Ernst, 2007; Loomis, Klatzky, & Lederman, 1991; Manyam, 1986; Millar & Al-Attar, 2005; Rock & Victor, 1964; Schultz & Petersik, 1994), and this difference in performance has been linked to differences in spatial acuity (i.e., the sharpness or detail of its resolution). For example, when a three-dimensional stimulus was presented to participants, people's ability to discriminate small changes in height was better for visual than haptic perception (Helbig & Ernst, 2007; see also Ernst & Banks, 2002). Only when the visual presentation was blurred (i.e., artificially reducing its spatial acuity) did visual performance become worse than haptic performance. In other words, visual perception has the best spatial acuity of all human perceptual modalities, and so spatial representations resulting from vision have a level of specificity that is not found in spatial representations resulting from other perception. Therefore, the asymmetric effects of space on time found by Casasanto and colleagues may be due to the high spatial acuity from vision being relatively impervious to distortion rather than to an asymmetric mapping between domains.

In the present paper, we examined the interaction of time and space using touch rather than unimodal vision. Participants perceived spatial information regarding the length of a stick via haptic (i.e., tactile and proprioceptive) perception while concurrently perceiving a note for a particular duration. As in Casasanto and Boroditsky (2008), participants attended to both the spatial length and temporal duration in each trial and then reproduced either length or duration. If the spatial metaphor account is correct, one would expect space to affect time either unilaterally or to a greater extent than time affects space. Importantly, time is not predicted in this account to unilaterally affect space: any effects of time on spatial judgements would only “be compatible with our [metaphor] hypothesis so long as we also found a significantly *greater* effect of distance on time estimation” (Casasanto & Boroditsky, 2008, p. 590). In contrast, if the spatial representation account is correct, then whether time affects space depends on the relative acuity of spatial representations. Since spatial representations from haptic perception are of lower acuity than those from vision (Helbig & Ernst, 2007; Loomis et al., 1991; Schultz & Petersik, 1994), and are prone to distortion (Bhalla & Proffitt, 1999; Faineteau, Gentaz, & Viviani, 2003; Lederman, Klatzky, & Barber, 1985), we predicted that they would be susceptible to interference from concurrent temporal information. Furthermore, spatial representations of relatively low acuity (i.e., haptic) may not be able to distort time as effectively as those of high acuity (i.e., visual). Thus, when spatial information relies on touch, we expected the effect of time on space to be substantially stronger than the effects of space on time.

Moreover, any modulation of space–time interaction (or lack thereof) by the modality of spatial perception has theoretical impact beyond distinguishing between the spatial metaphor and spatial representation accounts of mental time. Much research on time perception has focused not on the mental representation of time, but rather on the psychophysical structures and mechanisms that underlie timing processes, such as the biological pacemaker of an internal clock (e.g., Gibbon, Church, & Meck, 1984; Treisman, 1963; Wearden, 2003; see Allman, Teki, Griffiths, & Meck, 2014; Grondin, 2010, for reviews). These psychophysical perspectives on time perception are closely linked to models of animal timing and tend to focus on phenomena that alter the speed of the pacemaker, such as heat (e.g., Wearden & Penton-Voak, 1995) or repetitive stimulation (e.g., Treisman & Brogan, 1992), but cannot explain how concurrent *spatial* information interferes with timing. Finding that the directionality and effect size of time–space interference varies by modality would be informative about the processes that people engage to make temporal judgements. We return to this issue in the general discussion.

## 2. Experiment 1

In this study, people were presented with a stick that they could touch but not see, so information regarding spatial length was haptically (but not visually) perceived while hearing a concurrent note for a particular duration. We then asked participants to reproduce either the spatial length of the stick by holding their hands apart (still with no visual feedback) or the temporal duration of the note by holding down a button. Following the spatial representation account, we expected concurrent temporal duration to affect the reproduction of spatial length, but for concurrent spatial information to have limited or no effects at all on the reproduction of duration.

### 2.1. Method

#### 2.1.1. Participants

Thirty-two right-handed native speakers of English were recruited from the University of Manchester community (30 women, mean age = 19.2). They all had normal or corrected-to-normal vision and had no hearing impairments. Participants received £5 or course credits for their participation.

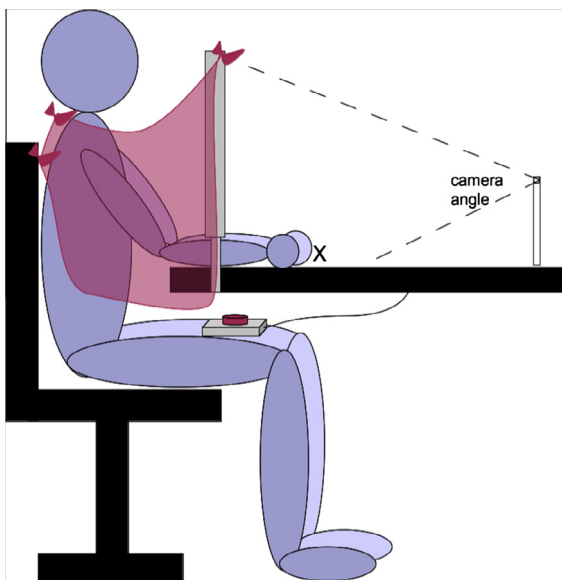
#### 2.1.2. Materials

Eight rigid, hollow plastic sticks (ca. 16 mm in diameter) were divided into varying lengths (100–450 mm in steps of 50 mm). Eight sine waveform notes of 440 Hz were created in varying durations (1000–4500 ms in steps of 500 ms) with Audacity (version 1.2.6). Crossing stick lengths with note durations, we created 64 stick-note stimulus sets. Each stimulus set was then combined with a length or duration reproduction task and divided into two stimulus lists, such that if a stimulus set occurred in List 1 with a length task, it occurred in List 2 with a duration task (i.e., task was counterbalanced across stick length

and note duration). Each list thus had 64 stick-note pairs, half with a length reproduction task and the other half with a duration reproduction task.

### 2.1.3. Procedure

Each participant was randomly assigned to one of the two stimulus lists and individually tested in a cubicle. The participant sat at a table with a response button box on his or her lap, and placed the hands and forearms through the gap at the bottom of a barrier, with a cape fastened around the neck to block all visual access to the hands and arms (see Fig. 1). During the testing procedure, the experimenter (first author) sat at right angles to the participant with a box to one side containing the eight sticks. The experiment was run with Superlab 4.0, with the order of trials individually randomized per participant. In each trial, the experimenter placed the relevant stick (as designated by the experimental programme) on the table and the participant pressed against the ends of the stick with index fingers; at point of contact, the experimenter pressed a key to begin playing the note. When the note stopped, the participant let go of the stick and withdrew the hands to the base of the barrier (i.e., to disrupt hand positioning so stick length was not passively preserved between the index fingers). The experimenter then returned the stick to the box and verbally instructed which judgement the participant was to make (as designated by the experimental programme). When the experimenter said “Time”, the participant held down a button on the response box (located on the lap) for the same duration as the note. When the experimenter said “Length”, the participant reached forward until their extended index fingers touched a board held up by the experimenter and then adjusted the distance between the index fingers to indicate



**Fig. 1.** Schematic of the experimental setup: ‘X’ marks the location of both haptic perception and reproduction of length. The cape and barrier (both opaque) were used in Experiments 1 and 3 to block visual access to spatial information, and were absent in Experiments 2 and 3 to allow access.

the length of the stick; the experimenter then removed the board and took a photograph of the hands’ position using a fixed camera. Use of the board (at location ‘X’ in Fig. 1) ensured that the participants’ hands were at a fixed distance from the camera. The photographs were taken at a resolution that allowed distance discrimination finer than 1 mm. Each participant performed a practice session of 4 trials, and the whole procedure lasted about 30 min.

### 2.1.4. Measures

Duration reproductions in milliseconds were measured from onset to release of the response button. Length reproductions were measured by the first author from digital photographs by randomly presenting each picture (condition-blind) and clicking on the centre of the left and right index fingertips; distance was calculated as the difference between *x*-coordinates. For reliability analysis, the second author blind-coded a random 12% sample of pictures: agreement between coders was very high ( $r = .999$ ) and accurate to within 1 mm distance. All references to length are in mm.

### 2.2. Results and discussion

We excluded failed trials in which the participant did not proceed as instructed (e.g., wrong keypresses; aborted trials), and then removed outliers more than 2.5 SDs from the mean for each length or duration condition. These criteria resulted in the exclusion of 1% and 2% of the length and duration reproduction trials, respectively.<sup>1</sup> We then calculated the mean reproduced length and duration per condition (e.g., mean reproduced duration after holding a 200 mm stick for 2500 ms), and conducted respective regression analyses, using the actual stimulus length and duration (i.e., stick length and note duration) as predictors. As the predicted effects were directional (e.g., reproduced length should increase as a function of stimulus duration), 1-tailed *t*-tests were conducted unless otherwise noted.

Table 1 gives results of all regression models. Reproduced length ( $R^2 = .997$ ,  $F(2,61) = 4519.07$ ,  $p < .001$ ) increased as a function of the actual stimulus length and, more importantly, as a function of stimulus duration. That is, sticks that were accompanied by a longer-duration note were judged to be longer in length, and sticks accompanied by a shorter-duration note were judged to be shorter in length (see Fig. 2). Conversely, although reproduced duration ( $R^2 = .993$ ,  $F(2,61) = 2225.74$ ,  $p < .001$ ) increased as a function of stimulus duration, it was unaffected by stimulus length. These results indicate that people’s judgements of spatial distance perceived through touch were influenced by their concurrent temporal experience, but not vice versa.

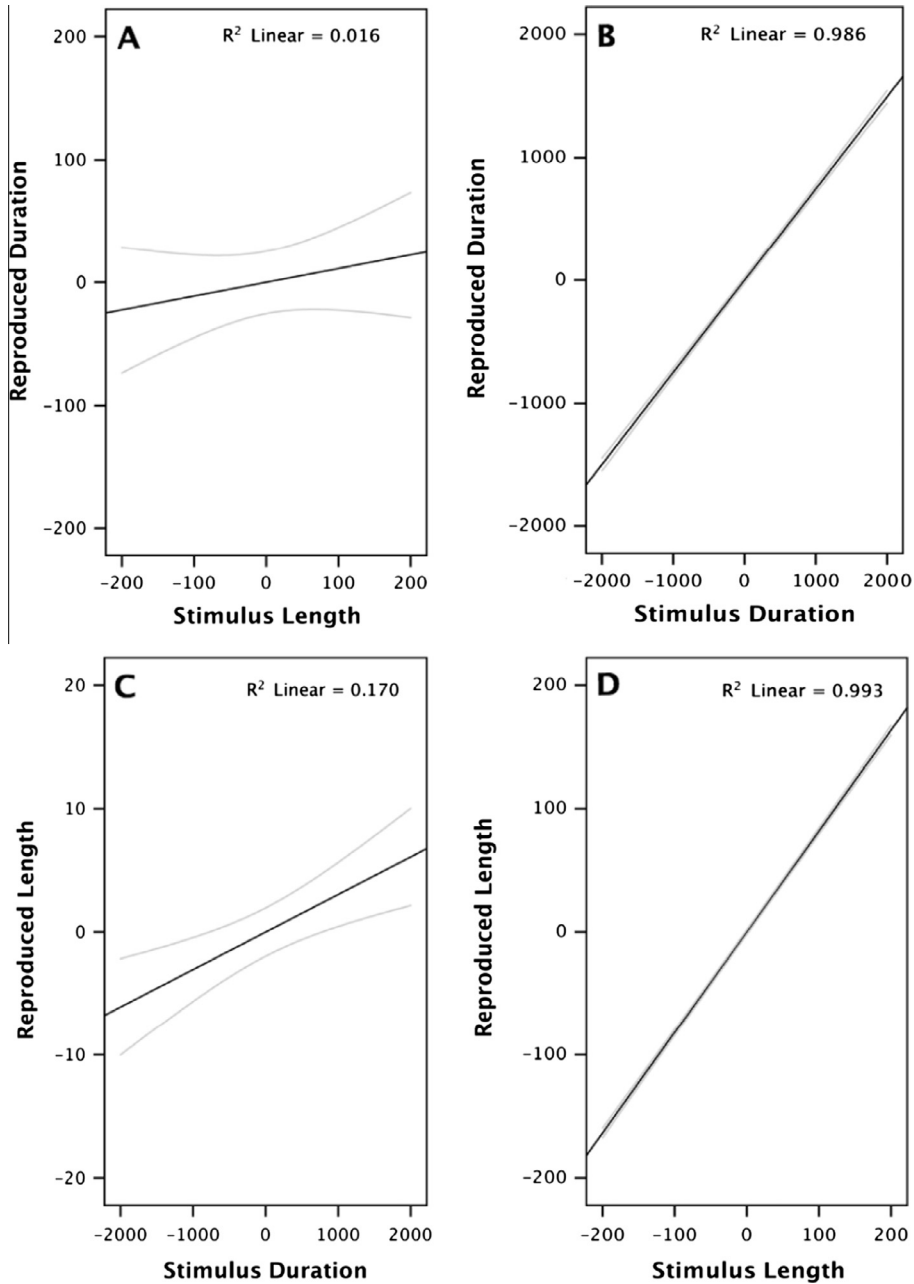
In order to contrast relative effect sizes (i.e., time on length versus length on time), we examined the extents

<sup>1</sup> In this and the following experiments, using Casasanto and Boroditsky’s (2008) participant exclusion criterion (i.e., excluding any participants whose coefficient fell below 0.5 in either the regression of reproduced duration on stimulus duration or reproduced length on stimulus length) made no difference to the pattern of results, and so we reported analyses of the full sample.

**Table 1**

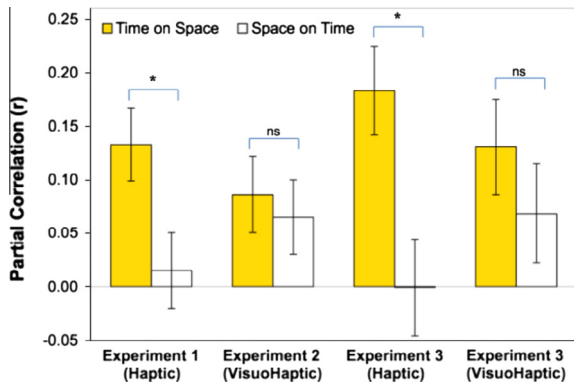
Reproduced length and duration as a function of actual stimulus length and duration in Experiment 1. Regression coefficients ( $\beta$ ) and their SE are unstandardized: see partial  $r$  for comparison of predictors.

Regression model	Predictor	$\beta$	SE	$t(61)$	$p$	Partial $r$
Reproduced length	Length	0.818	0.009	95.00	<.001	.997
	Duration	0.003	0.001	3.53	<.001	.412
Reproduced duration	Length	0.112	0.112	1.00	.161	.127
	Duration	0.747	0.011	66.71	<.001	.993



**Fig. 2.** Plots of the partial effects of stimulus length and duration on reproduced duration (panels A and B) and reproduced length (panels C and D) for haptic perception in Experiment 1. Grey lines indicate 95% CI.





**Fig. 3.** Effect sizes (mean participant partial correlations) of time on space and space on time in all experiments. Error bars show SE; \* represents a significant difference at  $p < .05$ .

to which the reproductions of length and duration were influenced by irrelevant information from the other dimension. To do this, we calculated partial correlations per dimension per participant, which allowed us to isolate the effect of actual time on reproduced length by partialling out actual length, and the effect of actual length on reproduced time by partialling out actual time. As predicted (see Fig. 3), the effect of time on space was significantly greater than the effect of space on time ( $t(31) = 2.42, p = .021$ ).

The results of the experiment support the spatial representation rather than spatial metaphor account of time. When space is haptically perceived, it does not affect time perception; instead, time interferes with the perception of haptic space. Our findings stand in direct contrast to those of previous studies that found visual space influenced time but not the other way around (Casasanto & Boroditsky, 2008; Casasanto et al., 2010) or that visual space influenced time to a larger extent than time did visual space (Merritt et al., 2010). These discrepancies can be attributed to the different acuities of spatial representations by modality, as haptic perception (as in our Experiment 1) leads to representations of lower spatial acuity than visual perception (as in previous studies), and hence are prone to distortion by temporo-spatial information to a greater extent. Such an account then predicts that if we also allow visual access to space (that is, participants visually and haptically perceive a stick for a given duration), we may be able to improve spatial acuity and hence weaken the effects observed in this experiment, such that the effect of time on space will no longer be greater than the effect of space on time. We test this hypothesis in Experiment 2.

### 3. Experiment 2

This study used the same paradigm as Experiment 1 with one exception: people were allowed to see as well as touch the stick, so information regarding spatial length was both haptically and visually perceived. As earlier discussed, the high-acuity modality of vision typically results in better spatial performance than the lower-acuity modality of touch. Similarly, bimodal perception through sight and touch is better than unimodal perception though

touch alone. When a stimulus is perceived visuohaptically, vision tends to dominate (e.g., Hartcher-O'Brien, Gallace, Krings, Koppen, & Spence, 2008; Posner, Nissen, & Klein, 1976; Rock & Victor, 1964). For example, participants tend to report only visual perception when a visual stimulus is simultaneously presented with a haptic stimulus (Hartcher-O'Brien et al., 2008). Moreover, visual access enhances the accuracy of haptic spatial perception (Ernst & Banks, 2002; Helbig & Ernst, 2007; Kennett, Taylor-Clarke, & Haggard, 2001; Millar & Al-Attar, 2005). When people had to discriminate small changes in the height of a three-dimensional stimulus, visuohaptic performance was close to that of unimodal vision, and both outperformed unimodal haptic perception (Helbig & Ernst, 2007; see also Ernst & Banks, 2002). When the visual presentation was blurred (i.e., artificially reducing its spatial acuity), visual performance deteriorated and visuohaptic performance was close to that of haptic. In other words, although a visuohaptic percept shows the influence of both modalities, people rely more heavily on vision to make spatial discriminations while it provides higher spatial acuity during typical conditions, and shift their reliance more to the haptic modality as spatial acuity of vision worsens. For these reasons, we expected the improved spatial acuity of visuohaptic perception in Experiment 2 to cause the differential effect sizes from Experiment 1 to converge. That is, we expected a weakened ability of temporal duration to affect length reproduction, and/or a strengthened ability of spatial length to affect duration reproduction, such that time may no longer affect space more than space affects time.

#### 3.1. Method

##### 3.1.1. Participants and materials

Twenty-six participants were recruited as in Experiment 1 (22 women, mean age = 19.3). The materials were the same as in Experiment 1.

##### 3.1.2. Procedure

The procedure was the same as in Experiment 1, except (1) the cape and barrier were removed (see Fig. 1) so that participants could see the stick as well as touch it, and see their hands when reproducing length; and (2) the stick was presented at jittered transverse positions in order to discourage participants from using the visual cues of the table (e.g., distance from side edge) when reproducing the length of the stick.

##### 3.1.3. Measures

As per Experiment 1. Double-coding of 15% of the lengths showed very high agreement between the two coders ( $r > .999$ ), accurate to within 1 mm distance.

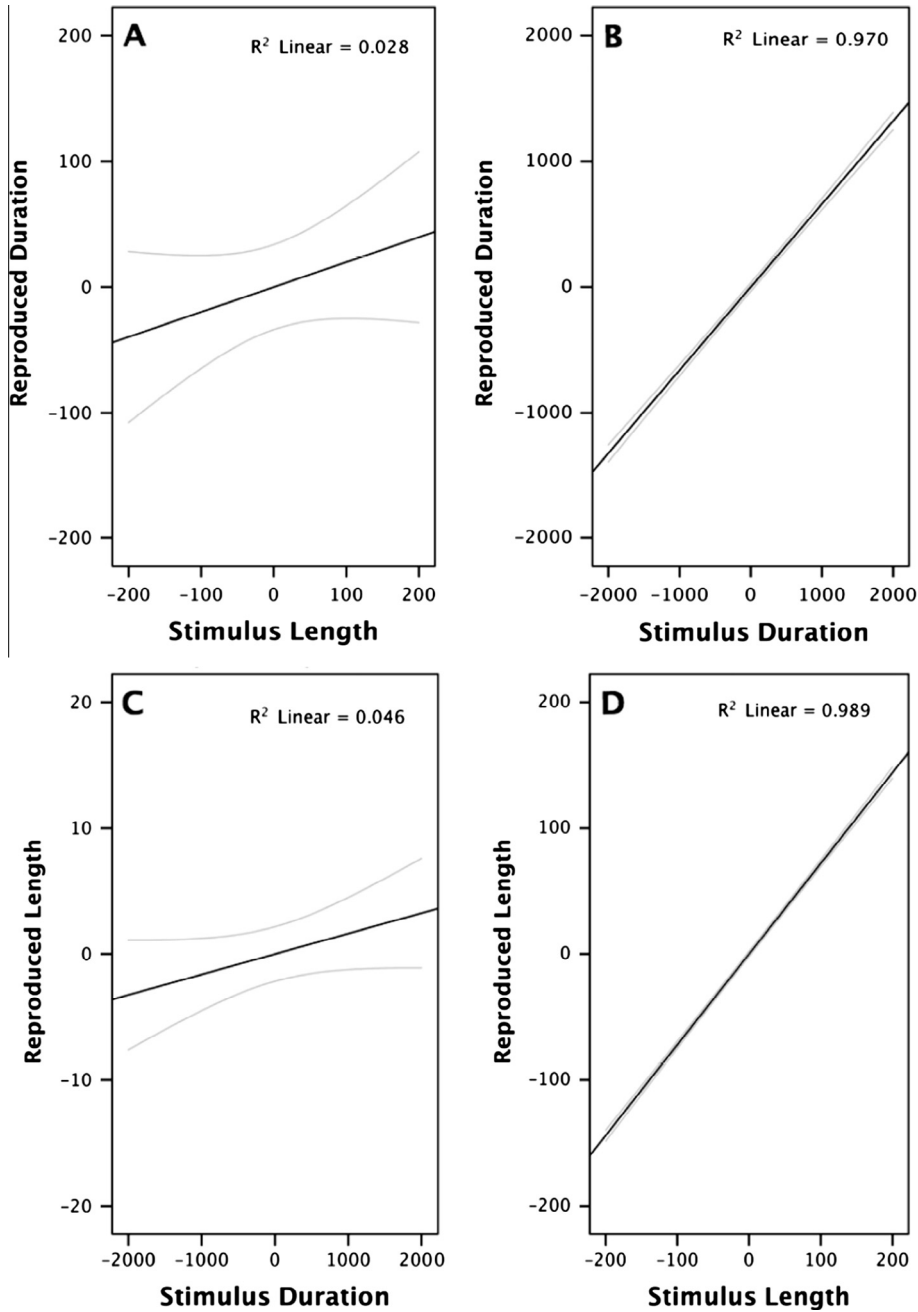
#### 3.2. Results and discussion

Removal of failed and outlier trials resulted in the exclusion of 1% and 2% of the length and duration reproduction trials, respectively. Results of the regressions are presented in Table 2. As before, reproduced length ( $R^2 = .995, F(2, 61) = 2864.94, p < .001$ ) increased as a func-

**Table 2**

Reproduced length and duration as a function of actual stimulus length and duration in Experiment 2. Regression coefficients ( $\beta$ ) and their *SE* are unstandardized: see partial *r* for comparison of predictors.

Regression model	Predictor	$\beta$	<i>SE</i>	<i>t</i> (61)	<i>p</i>	Partial <i>r</i>
Reproduced length	Length	0.721	0.010	75.68	<.001	.995
	Duration	0.002	0.001	1.71	.046	.213
Reproduced duration	Length	0.198	0.149	1.33	.094	.168
	Duration	0.660	0.015	44.38	<.001	.985



**Fig. 4.** Plots of the partial effects of stimulus length and duration on reproduced duration (panels A and B) and reproduced length (panels C and D) for visuo-haptic perception in Experiment 2. Grey lines indicate 95% CI.

tion of both stimulus length and duration, with good overall fit ( $R^2 = .995$ ,  $F(2,61) = 2864.94$ ,  $p < .001$ ). That is, participants' judgements of stick length were affected not only by its actual length but also by how long they spent holding it. Reproduced duration ( $R^2 = .985$ ,  $F(2,61) = 985.59$ ,  $p < .001$ ) increased as a function of actual stimulus duration and, this time, also marginally increased with stimulus length. That is, unlike Experiment 1, people's judgements of temporal duration showed a tendency, albeit a weak one, to be influenced by their concurrent visuohaptic spatial experience (see Fig. 4).

In order to examine whether the difference in relative effect sizes that we observed in Experiment 1 (i.e., time-on-length greater than length-on-time) disappeared in the presence of visuospatial perception, we again compared partial effects per participant per dimension. As we anticipated (see Fig. 3), the effect of time on space was approximately equivalent to the effect of space on time ( $t(25) = 0.96$ ,  $p = .339$ ).

Two observations in Experiment 2 are worth discussion. First, spatial representations from visuohaptic perception were still biased by concurrent temporal information. Second, when space is visuohaptically perceived, it has a weak effect on time perception to approximately the same extent as time interferes with the perception of visuohaptic space. The results of this study therefore fail to support the spatial metaphor account of time, which would have required the space-on-time effect to be greater than the time-on-space effect. Rather, our findings support the spatial representation account of time, and suggest that the ability of time and space to affect one another depends on the relative acuity of spatial representations. However, one further assumption of the spatial representation account remains to be tested. If haptic perception leads to lower-acuity spatial representations than visuohaptic perception (i.e., the theorised basis of the differential effects) then a person's spatial reproduction performance should be poorer under haptic than visuohaptic perception. To test this acuity assumption, and to replicate the novel findings in Experiments 1 and 2, we conducted a third experiment in which we manipulated the modality of spatial perception (i.e., haptic versus visuohaptic perception) within participants.

#### 4. Experiment 3

This final study used identical paradigms to the previous experiments in a blocked design that manipulated the modality of spatial perception within participants: people could only touch the stick in the haptic block, and could see as well as touch the stick in the visuohaptic block. We expected the haptic block to replicate the findings of Experiment 1 (space affects time more than time affects space), and the visuohaptic block to replicate the findings of Experiment 2 (space and time affect each other approximately equally). Critically, we could also test the acuity assumption of the spatial representation account by examining haptic and visuohaptic performance in accuracy of the spatial task. Since spatial representations from haptic perception are lower acuity than those from visuo-

haptic perception, we expected people to be less accurate at length reproduction in the haptic block than in the visuohaptic block.

#### 4.1. Method

##### 4.1.1. Participants and materials

Thirty-one participants were recruited as in Experiments 1 and 2 (21 women, mean age = 23.5). As participants in this experiment would perceive space both haptically and visuohaptically, the use of the full set of stimuli from Experiments 1 and 2 would have meant doubling the testing time of the experiment to 1 h, which we felt was excessive and likely to lead to fatigue effects. To overcome this problem, we removed the shortest and the longest length and duration conditions, resulting in 6 stick lengths (150–400 mm, with a step of 50 mm) and 6 note durations (1500–4000 ms, with a step of 500 ms). As in the previous experiments, each of the 36 stick-note stimulus sets was combined with a length and a duration reproduction task and divided into two lists such that a stimulus set was paired with a length reproduction task in one list and with a duration reproduction task in the other list. Thus, each list had 36 material sets, half with a length reproduction task and the other half with a duration reproduction task. We created two blocks (haptic and visuohaptic), each containing the same 36 material sets from the same stimulus list. The order of the blocks was counterbalanced across participants. Each participant performed a practice session of 8 trials (4 in each modality), and the whole procedure lasted about 40 min.

##### 4.1.2. Procedure

The procedure of the haptic block was the same as that in Experiment 1 (i.e., participants touched but did not see the stick) and the procedure of the visuohaptic block was the same as that in Experiment 2 (i.e., participants saw and touched the stick).

##### 4.1.3. Measures

As per Experiments 1 and 2. Double-coding of 11% of the reproduced lengths showed very high agreement between the two coders ( $r > .999$ ), accurate to within 1 mm distance.

#### 4.2. Results and discussion

Removal of failed and outlier trials resulted in the exclusion of 3% and 2% of the length and duration reproduction trials, respectively. As in Experiments 1 and 2, we conducted separate regression analyses on mean reproduced duration and length per condition, with predictors of stimulus length, stimulus duration, and modality of spatial perception (coded 0 for haptic, 1 for visuohaptic). Results can be seen in Table 3. Reproduced length ( $R^2 = .993$ ,  $F(3,68) = 1659.14$ ,  $p < .001$ ) increased overall with stimulus length and, critically, with stimulus duration, while modality of perception had no effect. Reproduced time ( $R^2 = .990$ ,  $F(3,68) = 1164.24$ ,  $p < .001$ ) increased as a function of stimulus duration but not length.



**Table 3**

Reproduced length and duration as a function of stimulus length, stimulus duration, and modality of perception (haptic versus visuohaptic) in Experiment 3. Regression coefficients ( $\beta$ ) and their *SE* are unstandardized: see partial *r* for comparison of predictors.

Regression model	Predictor	$\beta$	<i>SE</i>	<i>t</i> (61)	<i>p</i>	Partial <i>r</i>
Reproduced length	Length	0.877	0.012	70.47	<.001	.993
	Duration	0.004	0.001	3.28	<.001	.370
	Modality	−2.014	2.126	−0.95	.347	−.114
Reproduced duration	Length	0.140	0.129	1.08	.141	.130
	Duration	0.760	0.013	58.99	<.001	.990
	Modality	−76.580	22.014	−3.50	<.001	−.389

Note: *p*-values were based on 2-tailed *t*-tests for the modality effects, for which we did not have any directional prediction.

**Table 4**

Reproduced length and duration as a function of stimulus length and duration, separately for the haptic and visuohaptic modalities in Experiment 3. Regression coefficients ( $\beta$ ) and their *SE* are unstandardized: see partial *r* for comparison of predictors.

Modality	Regression model	Predictor	$\beta$	<i>SE</i>	<i>t</i> (33)	<i>p</i>	Partial <i>r</i>
Haptic	Reproduced length	Length	0.851	0.020	43.29	<.001	.991
		Duration	0.005	0.002	2.79	.004	.437
	Reproduced duration	Length	0.105	0.171	0.61	.272	.106
		Duration	0.726	0.017	42.33	<.001	.991
Visuohaptic	Reproduced length	Length	0.904	0.014	64.20	<.001	.996
		Duration	0.003	0.001	1.91	.033	.315
	Reproduced duration	Length	0.174	0.178	0.98	.168	.168
		Duration	0.795	0.018	44.60	<.001	.992

People produced longer durations overall for the haptic modality than the visuohaptic modality.

Separate analyses of the haptic block replicated the results of Experiment 1 (see Table 4 and Fig. 5). Reproduced length ( $R^2 = .991$ ,  $F(2,33) = 940.98$ ,  $p < .001$ ) increased as a function of both stimulus length and duration. That is, people's spatial judgements were affected by temporal information: the longer in time a stick was held, the longer in space it appeared to be. Reproduced duration ( $R^2 = .991$ ,  $F(2,33) = 895.92$ ,  $p < .001$ ) increased with stimulus duration, while stimulus length had no effect. Comparison of relative effect sizes via partial correlations showed that, for haptic perception of spatial information, the effect of time on space was significantly greater than the effect of space on time ( $t(30) = 3.16$ ,  $p = .004$ ; see Fig. 3).

Separate analysis of the visuohaptic block replicated the results of Experiment 2 (see Table 4 and Fig. 6). Reproduced length ( $R^2 = .996$ ,  $F(2,33) = 2062.44$ ,  $p < .001$ ) increased with both stimulus length and duration. As before, people's spatial judgements of length were influenced by temporal information. Reproduced time ( $R^2 = .992$ ,  $F(2,33) = 995.01$ ,  $p < .001$ ) increased as a function of stimulus duration, but not as a function of stimulus length. That is, the weak (marginal) effect of spatial length on time judgements that we observed in Experiment 2 did not emerge in the present experiment. Comparison of relative effect sizes confirmed that, as per Experiment 2, visuohaptic perception of spatial information led the effect of time on space to be approximately equivalent to the effect of space on time ( $t(30) = 1.66$ ,  $p = .108$ ; see Fig. 3).

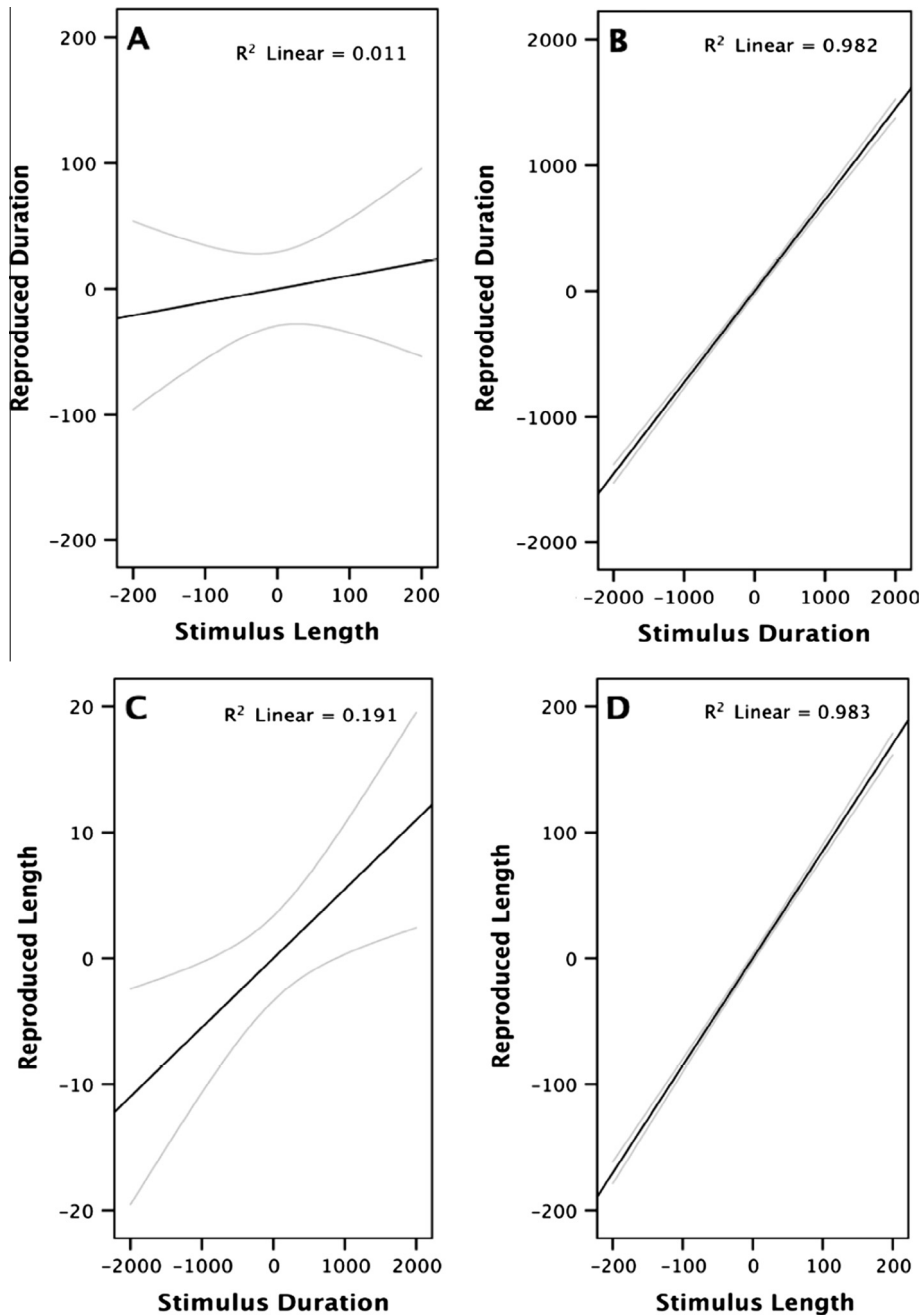
Finally, we examined whether spatial acuity differed across modalities by comparing partial effects of stimulus length on length reproduction. As expected, people were less accurate in length reproduction in the haptic block

(mean partial  $r = .946$ ,  $SE = .005$ ) than they were in the visuohaptic block (mean partial  $r = .976$ ,  $SE = .002$ ) ( $t(30) = 5.79$ ,  $p < .001$ ), which supports the hypothesis that the ability of time and space to affect one another depends on the spatial acuity of the representation.

Altogether, the findings of Experiment 3 support the spatial representation account of time, and fail to support the spatial metaphor account. Haptic perception produces a lower-acuity spatial representation than does visuospatial perception, which leads to differences in the ability of temporal and spatial information to influence one another. Time is able to affect haptic space more than haptic space is able to affect time. Time is also able to affect visuohaptic space, but no more strongly than visuohaptic space can affect time.

## 5. General discussion

In three experiments, we investigated whether the ability of time and space to influence one another depends on the spatial acuity of the representations in question. When spatial information relies on touch, the effect of time on space is substantially stronger than the effect of space on time. This finding is, to our best knowledge, the first clear demonstration of a *reverse* asymmetry between space and time (i.e., temporal information affects spatial judgements to a greater extent than spatial information affects temporal judgements). When spatial information relies on higher-acuity vision as well as touch, time affects space to roughly the same extent as space affected time (i.e., no asymmetry between spatial and temporal dependencies). These findings of reverse and null asymmetry are therefore inconsistent with the spatial metaphoric mapping account of time representation (Casasanto & Boroditsky, 2008;

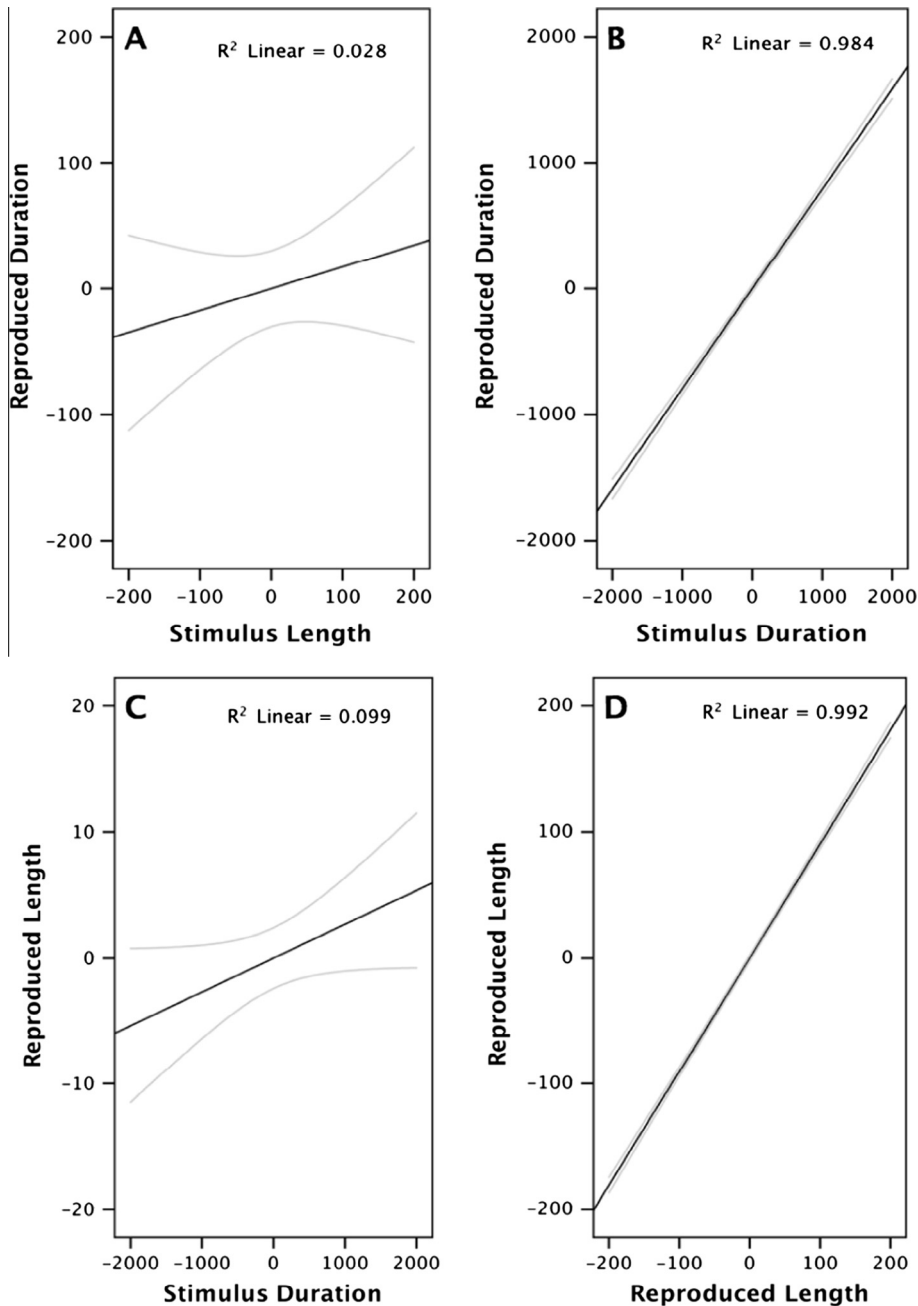


**Fig. 5.** Plots of the partial effects of stimulus length and duration on reproduced duration (panels A and B) and reproduced length (panels C and D) for the haptic block in Experiment 3. Grey lines indicate 95% CI.

Casasanto et al., 2010; Merritt et al., 2010), according to which space should always have a greater effect on time than time on space because temporal thinking metaphorically employs spatial representations. Instead, our findings are more consistent with the spatial representation account, according to which space and time share a common representation that is subject to interference from either direction.

The spatial representation account thus allows for a two-way interdependence between time and space, which

is mediated by the acuity of the sensory modality in which space is perceived. When space is perceived via touch, the relatively low acuity of the spatial representation fails to bias the representation of time, but is instead prone to interference from concurrent temporal information: hence, the perception of haptic space is unilaterally affected by time, as we showed in Experiments 1 and 3. When space is perceived visually in addition to touch, it increases the spatial acuity of the representation such that the reverse asymmetric effects found for haptic perception begin to



**Fig. 6.** Plots of the partial effects of stimulus length and duration on reproduced duration (panels A and B) and reproduced length (panels C and D) for the visuohaptic block in Experiment 3. Grey lines indicate 95% CI.

converge. The higher acuity of visuohaptic spatial representation exerts at best a weak influence on time (Experiments 2), while still being susceptible to interference from temporal information: hence, time and visuohaptic space affect each other to a similar extent.

But why did we not observe as strong an effect of *visuohaptic* space on time as previous studies have shown for *visual* space on time (e.g., Cai et al., 2013; Casasanto & Boroditsky, 2008; Xuan et al., 2007)? One possibility is that, in our experiments, the acuity of visuohaptic percep-

tion is lower than that of visual perception because attention has to be split between vision and touch. Such a possibility, however, would be contrary to previous findings that visuohaptic spatial perception tends to be as good as, if not sometimes better than, unimodal vision (Ernst & Banks, 2002; Helbig & Ernst, 2007; Kennett et al., 2001; Millar & Al-Attar, 2005). Another possibility is that the length reproduction component of the task may have led people to rely more on the haptic modality than would be typical in visuohaptic perception. Participants in our

experiments knew they would reproduce length using the same visuohaptic modalities they used to perceive it (as participants in [Casasanto and Boroditsky's \(2008\)](#), experiments knew they would reproduce length using the same visual modality they used to perceive it), which might have allowed the lower-acuity modality of touch to contribute more to the spatial representation of length than if the reproduction task were not present. How space–time interaction varies according to the modality of spatial perception versus reproduction deserves further investigation.

It should be noted that space–time interaction may arise from other shared dimensions such as quantity or magnitude, on which space and time are closely interconnected (e.g., *more* space travelled in *more* time). In other words, the underlying representation of both space and time (and number) may be magnitude-based ([Buetti & Walsh, 2009](#); [Burr et al., 2010](#); [Gallistel & Gelman, 2000](#); [Lambrechts et al., 2013](#); [Walsh, 2003](#)), which therefore gives rise to the bi-directional interaction between space and time. Though such an account is compatible with our data, it would require that magnitude information from haptic space be less acute than magnitude information from visual space, an assumption that has yet to be tested. The spatial representation account of time that we put forward here can explain the current effects in terms of differential perceptual acuity without positing a pure magnitude system.

One central weakness of the spatial representation account of time–space relations (in common with the spatial metaphor account) is that, in focusing on the conceptual representation of time, it does not provide a psychophysical model of how and where the space–time interaction arises during processing of temporal duration. However, we believe these conceptual and psychophysical accounts of time processing can be reconciled. In related work ([Cai, Connell, & Connell, in preparation](#); [Cai, Wang, & Connell, in preparation](#)), we have made one of the first attempts to localize conceptual time–space effects in the mechanistic framework of the internal clock model ([Allman et al., 2014](#); [Gibbon et al., 1984](#); [Treisman, 1963](#); see also [Cai & Wang, 2014](#), for a related proposal concerning time and number). According to this model, a given duration is registered as the accumulation of pulses emitted by a central pacemaker (whose rate may vary; [Meck & Church, 1987](#); [Treisman & Brogan, 1992](#)). The temporal representation (i.e., number of pulses) is then stored in memory for later retrieval, such as in a time reproduction task. While being kept in memory, the temporal representation is susceptible to interference ([Grondin, 2005](#); [Jazayeri & Shadlen, 2010](#); [Jones & Wearden, 2004](#)). We hypothesized that spatial processing does not affect the pacemaker or actual duration perceived, but rather that spatial representations of visual length can interfere with temporal representations of duration while both concurrently reside in memory because they share a common format. According to this account, lines of varying length should affect time reproduction only if displayed when a given duration is first presented, but should have no effect if displayed during the time reproduction task because length and duration representations have no opportunity

at that point to co-reside in memory; these predictions were confirmed by [Cai and Connell's \(2014\)](#) experiments. In addition, [Cai et al. \(in preparation\)](#) provided evidence that space–time interaction is a result of interference between spatial and temporal representations being held in short-term memory, as opposed to interference occurring at the point of spatial or temporal encoding. Together, these studies support the integrated account of time perception that localizes space-on-time conceptual effects in the memory component of the internal clock model.

The findings of the present paper also fit this integrated account, whereby duration representations can interfere with spatial representations from haptic and visuohaptic perception while both concurrently reside in short-term memory. Furthermore, the current studies extend this account by showing that different modalities of spatial perception (e.g., unimodal visual, unimodal haptic, bimodal visuohaptic) may result in spatial representations that have differential ability to bias, and differential susceptibility to be biased by, representations of other dimensions. In particular, it is likely that the high spatial acuity of vision makes it easy to bias time representations, while remaining relatively impervious to interference from concurrent temporal information; hence the strong effects of visual space on time alongside null or limited effects in the other direction (e.g., [Casasanto & Boroditsky, 2008](#); [Merritt et al., 2010](#)). By comparison, the lower acuity of haptic perception leads to a somewhat noisier spatial representation, which is less able to bias time representations and more prone to temporal interference; hence the negligible effects of haptic space on time yet clear effects of time on haptic space (Experiments 1 and 3). Finally, the reasonably good spatial acuity of visuohaptic perception means it is able to bias time representations, while still remaining susceptible to temporal interference; hence the roughly equal effects that visuohaptic space and time have on one another (Experiments 2 and 3). The integrated account of time perception ([Cai & Connell, 2014](#); [Cai et al., in preparation](#)) can encompass such a flexible pattern of effects by allowing the relative acuity (i.e., precision) of spatial representations, which varies by the modality of perception, to determine whether they have the power to interfere with temporal representations as they reside together in short-term memory. Future research should investigate how the ability of various dimensions (e.g., numerosity, number, size; see [Xuan et al., 2007](#)) to bias time representations may also vary by the modality of perception, and, conversely, whether temporal interference on other dimensions is modulated by the modality of time perception (e.g., a duration presented visually, auditorily, or haptically).

In conclusion, the present experiments show that time is not asymmetrically dependent on space, and hence offer evidence against the spatial metaphor account of time representation. Rather, time and space share a common spatial representation, which allows time to *affect* spatial information that emerges from relatively low-acuity perceptual modalities like touch, and time to *be affected by* spatial information from relatively high-acuity perceptual modalities like vision.

## Acknowledgements

This work was supported in part by a research project grant from the Leverhulme Trust (F/00 120/CA).

## References

- Allman, M. J., Teki, S., Griffiths, T. D., & Meck, W. H. (2014). Properties of the internal clock: First- and second-order principles of subjective time. *Annual Review of Psychology*, *65*, 743–771.
- Assmus, A., Marshall, J., Noth, J., Zilles, K., & Fink, G. (2005). Difficulty of perceptual spatiotemporal integration modulates the neural activity of left inferior parietal cortex. *Neuroscience*, *132*, 923–927.
- Assmus, A., Marshall, J. C., Ritzl, A., Noth, J., Zilles, K., & Fink, G. R. (2003). Left inferior parietal cortex integrates time and space during collision judgments. *NeuroImage*, *20*, S82–S88.
- Barsalou, L. W., & Wiemer-Hastings, K. (2005). Situating abstract concepts. In D. Pecher & R. A. Zwaan (Eds.), *Grounding cognition: The role of perception and action in memory, language, and thought* (pp. 129–163). New York: Cambridge University Press.
- Basso, G., Nichelli, P., Frassinetti, F., & di Pellegrino, G. (1996). Time perception in a neglected space. *Neuroreport*, *7*, 2111–2114.
- Bhalla, M., & Proffitt, D. R. (1999). Visual-motor recalibration in geographical slant perception. *Journal of Experimental Psychology: Human Perception and Performance*, *25*, 1076–1096.
- Boroditsky, L. (2000). Metaphoric structuring: Understanding time through spatial metaphors. *Cognition*, *75*, 1–28.
- Bryant, D. J. (1992). A spatial representation system in humans. *Psychology*, *3*(16), space 1.
- Buetti, D., & Walsh, V. (2009). The parietal cortex and the representation of time, space, number and other magnitudes. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*, 1831–1840.
- Burr, D. C., Ross, J., Binda, P., & Morrone, M. C. (2010). Saccades compress space, time and number. *Trends in Cognitive Sciences*, *14*, 528–533.
- Cai, Z. G., & Connell, L. (2014). On magnitudes in memory: An internal clock account of the effect of space on time. Manuscript submitted for publication.
- Cai, Z. G., Connell, L., & Holler, J. (2013). Time does not flow without language: Spatial distance affects temporal duration regardless of movement or direction. *Psychonomic Bulletin and Review*, *20*, 973–980.
- Cai, Z. G., Wang, R., & Connell, L. (2014). *Space-time interaction arises from memory interference*. Manuscript in preparation.
- Cai, Z. G., & Wang, R. (2014). Numerical magnitude affects temporal memories but not time encoding. *PLoS ONE*, *9*, e83159.
- Casasanto, D., & Boroditsky, L. (2008). Time in the mind: Using space to think about time. *Cognition*, *106*, 579–593.
- Casasanto, D., Fotakopoulou, O., & Boroditsky, L. (2010). Space and time in the child's mind: Evidence for a cross-dimensional asymmetry. *Cognitive Science*, *34*, 387–405.
- Cattaneo, Z., & Vecchi, T. (2008). Supramodality effects in visual and haptic spatial processes. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*, 631.
- Clark, H. H. (1973). Space, time, semantics, and the child. In T. E. Moore (Ed.), *Cognitive development and the acquisition of language* (pp. 27–63). New York: Academic Press.
- Connell, L., Cai, Z. G., & Holler, J. (2013). Do you see what I'm singing? Visuospatial movement biases pitch perception. *Brain and Cognition*, *81*, 124–130.
- Danckert, J., Ferber, S., Pun, C., Broderick, C., Striemer, C., Rock, S., et al. (2007). Neglected time: Impaired temporal perception of millisecond intervals in unilateral neglect. *Journal of Cognitive Neuroscience*, *19*, 1706–1720.
- DeLong, A. J. (1981). Phenomenological space-time: Toward an experiential relativity. *Science*, *213*, 681–683.
- Ernst, M. O., & Banks, M. S. (2002). Humans integrate visual and haptic information in a statistically optimal fashion. *Nature*, *415*, 429–433.
- Faineteau, H., Gentaz, E., & Viviani, P. (2003). The kinaesthetic perception of Euclidean distance: A study of the detour effect. *Experimental Brain Research*, *152*, 166–172.
- Frassinetti, F., Magnani, B., & Oliveri, M. (2009). Prismatic lenses shift time perception. *Psychological Science*, *20*, 949–954.
- Gallistel, C. R., & Gelman, R. (2000). Non-verbal numerical cognition: From reals to integers. *Trends in Cognitive Sciences*, *4*, 59–65.
- Gibbon, J., Church, R. M., & Meck, W. H. (1984). Scalar timing in memory. *Annals of the New York Academy of Sciences*, *423*, 52–77.
- Gibbs, R. (2006). *Embodiment and cognitive science*. New York: Cambridge University Press.
- Gibbs, R. W. (1994). Figurative language understanding: A special process. In R. W. Gibbs (Ed.), *The poetics of mind: Figurative thought, language, and understanding* (pp. 80–119). Cambridge: Cambridge University Press.
- Giudice, N. A., Betty, M. R., & Loomis, J. M. (2011). Functional equivalence of spatial images from touch and vision: Evidence from spatial updating in blind and sighted individuals. *Journal of Experimental Psychology: Learning Memory, and Cognition*, *37*, 621–634.
- Giudice, N. A., Klatzky, R. L., & Loomis, J. M. (2009). Evidence for amodal representations after bimodal learning: Integration of haptic-visual layouts into a common spatial image. *Spatial Cognition and Computation*, *9*, 287–304.
- Grondin, S. (2005). Overloading temporal memory. *Journal of Experimental Psychology: Human Perception and Performance*, *31*, 869–879.
- Grondin, S. (2010). Timing and time perception: A review of recent behavioral and neuroscience findings and theoretical directions. *Attention, Perception, & Psychophysics*, *72*, 561–582.
- Hartcher-O'Brien, J., Gallace, A., Krings, B., Koppen, C., & Spence, C. (2008). When vision 'extinguishes' touch in neurologically-normal people: Extending the Colavita visual dominance effect. *Experimental Brain Research*, *186*, 643–658.
- Helbig, H. B., & Ernst, M. O. (2007). Optimal integration of shape information from vision and touch. *Experimental Brain Research*, *179*, 595–606.
- Jazayeri, M., & Shadlen, M. N. (2010). Temporal context calibrates interval timing. *Nature Neuroscience*, *13*, 1020–1026.
- Jones, L. A., & Wearden, J. H. (2004). Double standards: Memory loading in temporal reference memory. *Quarterly Journal of Experimental Psychology Section B*, *57*, 55–77.
- Kennett, S., Taylor-Clarke, M., & Haggard, P. (2001). Noninformative vision improves the spatial resolution of touch in humans. *Current Biology*, *11*, 1188–1191.
- Kosslyn, S. M., Ball, T. M., & Reiser, B. J. (1978). Visual images preserve metric spatial information: Evidence from studies of image scanning. *Journal of Experimental Psychology: Human Perception and Performance*, *4*, 47–60.
- Lacey, S., Campbell, C., & Sathian, K. (2007). Vision and touch: Multiple or multisensory representations of objects? *Perception*, *36*, 1513–1521.
- Lakoff, G., & Johnson, M. (1980). *Metaphors we live by*. Chicago and London: The University of Chicago Press.
- Lakoff, G., & Johnson, M. (1999). *Philosophy in the flesh: The embodied mind and its challenge to western thought*. Chicago: University of Chicago Press.
- Lambrechts, A., Walsh, V., & van Wassenhove, V. (2013). Evidence accumulation in the magnitude system. *PLoS ONE*, *8*(12), e82122.
- Lederman, S. J., Klatzky, R. L., & Barber, P. (1985). Spatial and movement-based heuristics for encoding pattern information through touch. *Journal of Experimental Psychology: General*, *114*, 33–49.
- Loomis, J. M., Klatzky, R. L., & Lederman, S. J. (1991). Similarity of tactual and visual picture recognition with limited field of view. *Perception*, *20*, 167–177.
- Manyam, V. J. (1986). A psychophysical measure of visual and kinaesthetic spatial discriminative abilities of adults and children. *Perception*, *15*, 313–324.
- Meck, W. H., & Church, R. M. (1987). Nutrients that modify the speed of internal clock and memory storage processes. *Behavioral Neuroscience*, *101*, 465–475.
- Merritt, D. J., Casasanto, D., & Brannon, E. M. (2010). Do monkeys think in metaphors? Representations of space and time in monkeys and humans. *Cognition*, *117*, 191–202.
- Millar, S., & Al-Attar, Z. (2005). What aspects of vision facilitate haptic processing? *Brain and Cognition*, *59*, 258–268.
- Oliveri, M., Koch, G., & Caltagirone, C. (2009). Spatial-temporal interactions in the human brain. *Experimental Brain Research*, *195*, 489–497.
- Parkinson, C., Liu, S., & Wheatley, T. (2014). A common cortical metric for spatial, temporal, and social distance. *Journal of Neuroscience*, *34*, 1979–1987.
- Posner, M. I., Nissen, M. J., & Klein, R. M. (1976). Visual dominance: An information-processing account of its origins and significance. *Psychological Review*, *83*, 157.
- Renier, L. A., Anurova, I., De Volder, A. G., Carlson, S., VanMeter, J., & Rauschecker, J. P. (2009). Multisensory integration of sounds and vibrotactile stimuli in processing streams for "what" and "where". *Journal of Neuroscience*, *29*, 10950–10960.
- Rock, I., & Victor, J. (1964). Vision and touch: An experimentally created conflict between the two senses. *Science*, *143*, 594–596.
- Röder, B., & Rösler, F. (1998). Visual input does not facilitate the scanning of spatial images. *Journal of Mental Imagery*, *22*, 165–182.

- Schultz, L. M., & Petersik, J. T. (1994). Visual–haptic relations in a two-dimensional size-matching task. *Perceptual and Motor Skills*, 78, 395–402.
- Srinivasan, M., & Carey, S. (2010). The long and the short of it: On the nature and origin of functional overlap between representations of space and time. *Cognition*, 116, 217–241.
- Struiksma, M. E., Noordzij, M. L., & Postma, A. (2009). What is the link between language and spatial images? Behavioral and neural findings in the blind and sighted. *Acta Psychologica*, 132, 145–156.
- Treisman, M. (1963). Temporal discrimination and the indifference interval: Implications for a model of the “internal clock”. *Psychological Monographs*, 77, 1–31.
- Treisman, M., & Brogan, D. (1992). Time perception and the internal clock: Effects of visual flicker on the temporal oscillator. *European Journal of Cognitive Psychology*, 4, 41–70.
- Walsh, V. (2003). A theory of magnitude: Common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences*, 7, 483–488.
- Wearden, J. H. (2003). Applying the scalar timing model to human time psychology: Progress and challenges. In H. Helfrich (Ed.), *Time and mind II* (pp. 21–39). Göttingen: Hogrefe & Huber.
- Wearden, J. H., & Penton-Voak, I. S. (1995). Feeling the heat: Body temperature and the rate of subjective time, revisited. *Quarterly Journal of Experimental Psychology*, 48, 129–141.
- Xuan, B., Zhang, D., He, S., & Chen, X. (2007). Larger stimuli are judged to last longer. *Journal of Vision*, 7, 1–5.