Space-Time Interdependence and Sensory Modalities: Time Affects Space in the Hand But Not in the Eye

Zhenguang G. Cai (zhenguangcai@gmail.com)
Louise Connell (louise.connell@manchester.ac.uk)
School of Psychological Sciences, University of Manchester, Coupland 1, Oxford Road
Manchester, M13 9PL, UK

Abstract

Time and space are intimately related, but what is the real nature of this relationship? Is time mapped metaphorically onto space, or do the two domains share a common representational format? In the present paper, participants touched (but could not see) physical sticks while listening to an auditory note. Judgements of stick length were affected by concurrent note duration, but not vice versa. When participants were allowed to see as well as touch the sticks, however, the effects reversed. These findings run counter to the spatial metaphor account of time, which claims that effects of space on time should always be stronger than those of time on space. Rather, our findings support the spatial representation account, in which time and space share a common neural substrate that may be affected by concurrent temporal or spatial information, depending on the perceptual acuity of the modality used to perceive space.

Keywords: Time; space; representation; haptic perception; visual perception; sensory dominance; metaphor

Though our immediate perception of the world is limited to our senses such as vision and hearing, we use these senses to perceive and represent other dimensions of the world besides colours and sounds. For instance, we can perceive the spatial information of an object (e.g., its length, height and size) by looking at it or touching it. 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; Gibbs, 2006; 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 5 minutes from the airport*). A range of studies has provided evidence that these linguistic expressions reflect a deeper conceptual bridge between time and space. For example, people perceive the passage of time either as if they are moving in space towards the future, or as if the future is moving towards them (e.g., Boroditsky & Ramscar, 2002; McGlone & Harding, 1998). Other studies have shown that space affects the perception of temporal 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), with a larger square than a smaller one (Xuan, Zhang, He, & Chen, 2007), and with 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; 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).

Alternatively, according to the *spatial representation* account of time, temporal and spatial information are processed in a common neural substrate and share representational and attentional resources. Time is closely related to space in action and perception (e.g., Walsh, 2003): 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). Thus, temporal duration and spatial distance may share a representational format (e.g., Locke, 1689/1995), 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 (Burr, Ross, Binda & Morrone, 2010; Walsh, 2003), but a weaker version of the spatial representation theory of time does not necessarily require the magnitude assumption. Critically, 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 the effects of time on space to be as strong as or stronger than the effects of space on time, depending on factors 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 and then asked them to reproduce either the length of the line or its duration of presentation. 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. Furthermore, the same pattern emerged whether the line was static or grew to its full length, when the line was replaced with a moving dot, or when a concurrent auditory note provided an additional source of temporal information. A later variant of this nonlinguistic task, 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), 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 are rather 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). Visual perception has the best spatial acuity (i.e., the sharpest or most detailed resolution) 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 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, any effects of time on spatial judgements should be substantially weaker than the usual effects of space on temporal judgements. In contrast, if the spatial representation account is correct, then whether time affects space depends on the relative acuity of spatial representations. Though space can be perceived either visually or haptically, research has suggested that haptic-spatial representations are more prone to distortion than those of vision (e.g., Lederman, Klatsky & Barber, 1985); hence, we predicted that haptic space would be susceptible to interference from concurrent temporal information. Furthermore, since haptic-spatial representations are less acute than visuo-spatial representations (e.g., Schultz & Petersik, 1994), they may not be able to distort time as visuo-spatial representations do. 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.

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 spatial concurrent information to have limited or no effects at all on the reproduction of duration.

Method

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

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 32 stick-note pairs, half with a length task and the other half with a duration task.

Procedure Each participant was 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 Figure 1). During the testing procedure, the experimenter (first author) sat at right angles to the participant and had 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 they touched a board held up by the experimenter) and indicated the length of the stick between the index fingers; 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 Figure 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 before the real experiment, and the whole procedure lasted about 30 minutes.

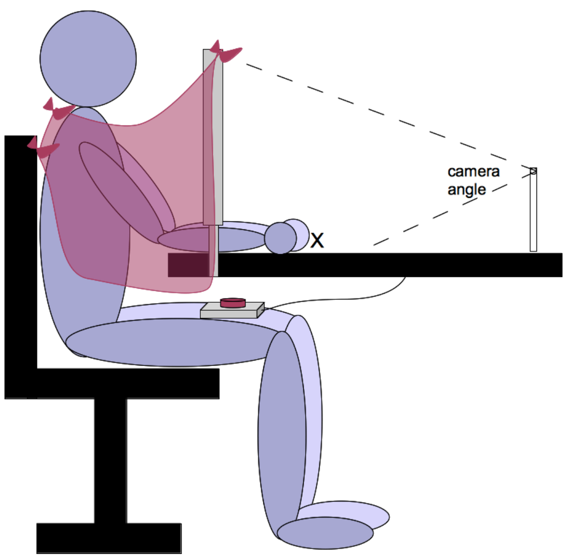


Figure 1: Schematic of the experimental setup: 'X' marks the location of both haptic perception and reproduction of length. The cape and barrier (both opaque) were used in Experiment 1 to block visual access to spatial information, and were absent in Experiment 2 to allow access.

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 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.

Design & Analysis We excluded failed trials in which the participant did not proceed as instructed (e.g., wrong key presses; missed trials), and then removed outliers more than 2.5 SDs away from the mean for each length or duration condition. The data trimming resulted in the exclusion of less than 2% of either the length or duration trials. Following the criterion in Casasanto and Boroditsky (2008, p. 581), two participants who did poorly in either the length or duration judgements (i.e., when the regression coefficient fell below 0.5 in either the regression of reproduced durations with note duration or reproduced lengths with stick length) were excluded from the analysis.[1] We then used linear mixed effects (LME) modelling to analyse condition means for each participant (e.g., average reproduced duration per participant was regressed on each different stick length). The final model always included the fixed effect; the random effects always included the participant intercept.[2] Regression coefficients are reported as unstandardised β values with standard errors.

Results and discussion

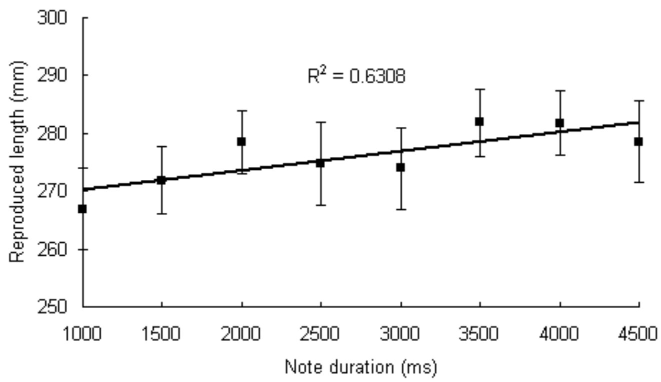
Reproduced length was significantly affected by experienced duration, $\beta = 0.0033$, $SE = 0.0015$, $t(209) = 2.27$, $p = .024$, but reproduced duration was unaffected by stick length, $\beta = 0.113$, $SE = 0.114$, $t(209) = 0.99$, $p = .324$. Sticks that were accompanied by a longer duration note were judged to be longer in length, and sticks accompanied by a shorter duration note were judged to be shorter in length (see Figure 2). People's judgements of spatial distance perceived through touch were influenced by their temporal experience, but not vice versa. Both spatial and temporal estimates were highly accurate: reproduced durations were well predicted by actual note duration, $\beta = 0.771$, $SE = 0.014$, $t(209) = 53.56$, $p < .0001$, and reproduced lengths were well predicted by actual stick length, $\beta = 0.818$, $SE = 0.011$, $t(209) = 76.20$, $p < .0001$.

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 around (Casasanto & Boroditsky, 2008; Casasanto et al., 2010; Merritt et al., 2010). These

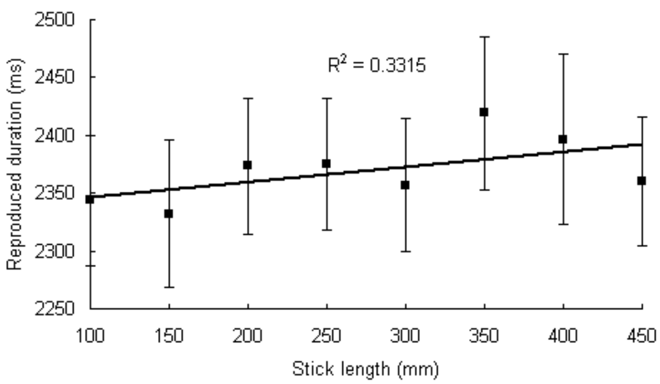
[1] The inclusion of these two participants did not change the statistical pattern of the results in this experiment.

[2] The random subject slope did not significantly contribute to the model fit in any of the LME analyses; thus, we did not include it as a random effect.

discrepancies can be attributed to the different acuities of spatial representations in different modalities, as haptic-spatial representations (as in our Experiment 1) are of lower acuity than visuo-spatial representations (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 space is visually perceived , the effects in Experiment 1 will be reversed. That is, highly acute visual perception of the stick will affect participants' time judgement, but spatiotemporal information will not be powerful enough to affect the vivid visuo-spatial memory in the length task. We test this hypothesis in Experiment 2.



A



B

Figure 2: Effects of time on space for haptic perception in Experiment 1 (A), with no corresponding effects of space on time (B). Error bars show one SE. R^2 fit is for graphed means.

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. Since the visual modality tends to be dominant in perception (e.g., participants tend to report only visual perception when a visual stimulus is simultaneously presented with a auditory or haptic stimulus: Colavita, 1974; Hartcher-O'Brien et al., 2008), we expected the high spatial acuity of vision in Experiment 2 to affect temporal judgements but not vice versa (i.e., a restoration of the usual asymmetric effect of space on time).

Method

Participants Twenty-six participants were recruited as in Experiment 1 (22 women, mean age = 19.3; six were later excluded from data analysis; see below).

Materials As per Experiment 1.

Procedure The procedure was the same as in Experiment 1, except 1) the cape and barrier were removed (see Figure 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 desk (e.g., distance from side edge) when reproducing the length of the stick.

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

Design & Analysis The same data trimming method as in Experiment 1 resulted in the removal of less than 2% of either the length or duration trials. Six participants were excluded according to the exclusion criterion adopted in Experiment 1.[3]

Results and discussion

Reproduced length was unaffected by experienced duration, β = 0.0016, *SE* = 0.0016, $t(139) = 0.98$, $p = .329$, but reproduced duration was significantly affected by stick length, β = 0.325, *SE* = 0.133, $t(139) = 2.44$, $p = .016$. Actual durations that were accompanied by shorter sticks were judged to take less time than durations that were accompanied by longer sticks (see Figure 3). People's judgements of time were influenced by their visual-haptic perception of spatial distance, but not vice versa. Both spatial and temporal estimates were again highly accurate: reproduced durations were well predicted by actual duration, β = 0.773, *SE* = 0.017, $t(139) = 43.72$, $p < .0001$, and reproduced lengths were well predicted by actual length, β = 0.739, *SE* = 0.010, $t(139) = 70.71$, $p < .0001$.

Results in Experiment 2 thus demonstrated that when space was perceived in vision, the effects in Experiment 1 were reversed; that is, visual space influenced time but not the other way round, just as found in previous studies by Casasanto and colleagues. As predicted by the spatial representation account of time, the ability of time to affect space depends on the relative acuity of spatial representations.

[3] Again, the inclusion of these 6 participants did not change the statistical pattern in the experiment.

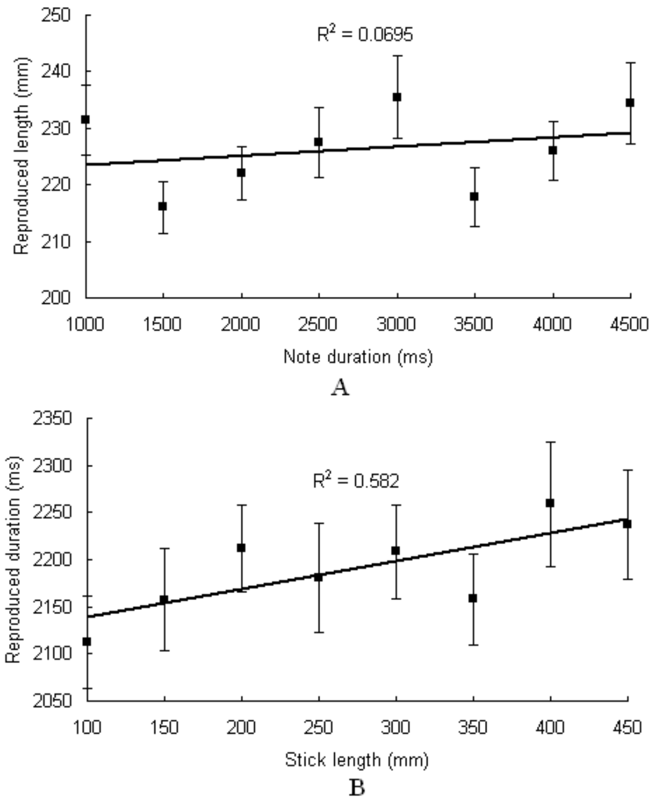


Figure 3: No effects of time on space for visuo-haptic perception in Experiment 2 (A), with instead effects of space on time (B). Error bars show one SE. R^2 fit is for graphed means.

General discussion

Two experiments revealed a double-disassociation of time and space effects according to sensory modality: time influenced haptic space but not the other way around, and visual space influenced time but not the other way round. The latter findings are in line with previous observations that time perception is subject to spatial interference (Casasanto & Boroditsky, 2008; DeLong, 1981; Xuan et al., 2007). However, when space is perceived haptically, concurrent spatial information fails to affect time perception; on the contrary, the perception of haptic space is influenced by concurrent temporal information. Such findings are, to our best knowledge, the first clear demonstration of a “reverse” asymmetry between space and time, i.e., time affects space to a greater extent than space affects time. This reverse asymmetry is therefore inconsistent with the spatial metaphoric mapping account of time representation (Casasanto & Boroditsky, 2008; Casasanto et al., 2010; Merritt et al., 2010), according to which space should always have a greater effect on time than time on space, as temporal perception 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. Highly sharp and stable visuo-spatial representations exert a strong influence on time judgements and are relatively impervious to temporal interference, while more distortable haptic-spatial representations are not acute enough to influence time and instead are prone to interference from temporal information. This spatial representation account is also consistent with the findings of Merritt et al. (2010), who found symmetric effects between space and time in rhesus monkeys but not in humans. Merritt et al argued that one explanation for the discrepancy between humans and monkeys is that human language facilitates the use of metaphoric mappings in spatial representations of time thinking; monkeys, lacking space-time metaphors, also lack asymmetric mappings between the domains. However, it is possible for human language to facilitate greater precision in visuo-spatial tasks without recourse to time-space metaphoric mappings. In their paradigm, Merritt and colleagues required participants to memorise two standard reference lines: one short (6 cm) and one long (24 cm). When later presented with another line, monkeys had only their visuo-spatial memory of the reference lines to help them decide if this new line was long or short, whereas humans also had a verbal numeric label available for what constituted long or short. Previous work has shown that availability of verbal numerical labels enhance accuracy in dot estimation tasks (Izard & Dehaene, 2008; Pica, Lemer, Izard, & Dehaene, 2004), and that verbal shadowing disrupts spatial memory in adults so that they show behaviour patterns similar to young children and rats (Hermer-Vasquez, Spelke, & Katnelson, 1999). It is therefore possible that availability of number words helped to preserve spatial acuity of the reference lines in humans (thus rendering spatial memory less susceptible to temporal interference), whereas lack of number words in monkeys allowed their spatial memory of the reference lines to be distorted by temporo-spatial information.

It should be noted that space-time interdependence 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 (Burr et al., 2010; Walsh, 2003), which therefore gives rise to the interdependence 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 magnitude system.

Finally, our study has implications beyond space-time interdependence. It suggests that previous findings of space-time asymmetry have more to do with differential acuity in perceiving space than the use of linguistic metaphor extending into nonlinguistic thought, thus casting considerable doubt on space-time asymmetric as evidence for the effects of language on thought (e.g., Boroditsky, 2000; Whorf, 1956). Furthermore, previous research has shown that visuo-spatial and haptic-spatial information are functionally equivalent (e.g., Guidice, et al, 2011), therefore suggesting a common storage (e.g., Lacey et al., 2007). Our findings lend further support to such a conclusion. That is, in order for time to interact with both haptic space and visual space, spatial information in these different modalities should be encoded in the same format.

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: time *affects* spatial information that emerges from relatively low-acuity perceptual modalities like touch, and time *is affected by* spatial information from relatively high-acuity perceptual modalities like vision.

Acknowledgments

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

References

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*. New York: Cambridge University Press.

Boroditsky, L. (2000). Metaphoric Structuring: Understanding time through spatial metaphors. *Cognition, 75*, 1-28.

Boroditsky, L., & Ramscar, M. (2002). The roles of body and mind in abstract thought. *Psychological Science, 13*, 185–189.

Bryant, D. J. (1992). A spatial representation system in humans. *Psycoloquy, 3*(16), space 1.

Burr, D. C., Ross, J., Binda, P., & Morrone, M. C. (2010). Saccades compress space, time and number. *Trends in Cognitive Sciences, 14*, 528-533.

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.

Colavita, F. B. (1974). Human sensory dominance. *Perception & Psychophysics, 16*, 409-412.

DeLong, A. J. (1981). Phenomenological space-time: toward an experiential relativity. *Science, 213*, 681-683.

Gibbs, R. (2006). *Embodiment and cognitive science*. New York: 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.

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.

Hermer-Vazquez, L., Spelke, E. S., & Katsnelson, A. S. (1999). Sources of flexibility in human cognition: Dual-task studies of space and language. *Cognitive Psychology, 39*, 3-36.

Izard, V., & Dehaene, S. (2008). Calibrating the mental number line. *Cognition, 106*, 1221–1247.

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.

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.

Locke, J. (1689/1995). *An essay concerning human understanding*. Amherst: Promethius Books.

McGlone, M. S., & Harding, J. L. (1998). Back (or forward?) to the future: The role of perspective in temporal language comprehension. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24*, 1211–1223.

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.

Pica, P., Lemer, C., Izard, V., & Dehaene, S. (2004). Exact and approximate arithmetic in an Amazonian indigene group. *Science, 306*, 499-503.

Schultz, L. M. & Petersik, J. T. (1994). Visual-haptic relations in a two-dimensional size matching task. *Perceptual and Motor Skills, 78*, 395-402.

Walsh, V. (2003). A theory of magnitude: common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences, 7*, 483-488.

Whorf, B. (1956). Language, Thought, and Reality: selected writings of Benjamin Lee Whorf, ed. J.B. Carroll. Cambridge, MA: MIT Press.

Xuan, B., Zhang, D., He, S., & Chen, X. (2007). Larger stimuli are judged to last longer. *Journal of Vision, 7*, 1-5.