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Cross-dimensional magnitude interactions arise from memory interference

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Abstract

Magnitudes from different dimensions (e.g., space and time) interact with each other in perception, but how these interactions occur remains unclear. In four experiments, we investigated whether cross-dimensional magnitude interactions arise from memory interference. In Experiment 1, participants perceived a constant-length line consisting of two line segments of complementary lengths and presented for a variable stimulus duration; then they received a cue about which of the two segment lengths to later reproduce. Participants were to first reproduce the stimulus duration and then the cued length. Reproduced durations increased as a function of the cued length if the cue was given before duration was retrieved from memory for reproduction (i.e. before duration reproduction; Experiment 1) but not if it was given after the duration memory had been retrieved from memory (i.e. after the start of duration reproduction; Experiment 2). These findings demonstrate that space-time interaction arises as a result of memory interference when length and duration information co-exist in working memory. Experiment 3 further demonstrated spatial interference on duration memories from memories of filled lengths (i.e. solid line segments) but not from noisier memories of unfilled lengths (demarcated empty spatial intervals), thus highlighting the role of memory noise in space-time interaction. Finally, Experiment 4 showed that time also exerted memory interference on space when space was presented as (relatively noisy) unfilled lengths. Taken together, these findings suggest that cross-dimensional magnitude interactions arise as a result of memory interference and the extent and direction of the interaction depend on the relative memory noises of the target and interfering dimensions. We propose a Bayesian model whereby the estimation of a magnitude is based on the integration of the noisily encoded percept of the target magnitude and the prior knowledge that magnitudes co-vary across dimensions (e.g., space and time). We discuss implications for cross-dimensional magnitude interactions in general.

Key words: space-time interaction; mental magnitude; memory interference; memory noise; Bayesian inference

1. Introduction

We perceive things as varying in quantity or magnitude along different dimensions such as volume (how big), spatial extent (how long/large), duration (how much time), and numerosity (how many). More often than not, different dimensions of a stimulus (an event or object) co-vary in magnitude such that a stimulus with “more stuff” in one dimension also has “more stuff” in another (e.g., if a journey is longer in length, it normally also takes more time to travel). Indeed, research has shown that magnitudes of a stimulus’ concurrent dimensions are somewhat coupled in our perception: if one dimension decreases or increases in its physical magnitude, the perceived magnitude of a concurrent dimension is accordingly affected. A stimulus with a larger spatial extent (e.g., length or size), for instance, is perceived to have a longer temporal extent (duration) (Binetti et al., 2015; Cai, Connell, & Holler, 2013; Casasanto & Boroditsky, 2008; DeLong, 1981; Xuan, Zhang, He, & Chen, 2007). Similarly, a duration is also perceived to be longer if it co-occurs with a larger-magnitude number or a larger numerosity of things (Cai & Wang, 2014; Chang, Tzeng, Hung Wu 2011; Dormal, Seron, & Pesenti, 2006; Oliveri et al., 2008; Xuan et al., 2007). These cross-dimensional magnitude interactions have been accounted for by assuming some commonality/association between different dimensions in their encoding (e.g., Walsh, 2003), their representations (e.g., Gallistel & Gelman, 2000), or their responses (e.g., Yates, Loetscher, & Nicholls, 2012). As we will see below, depending on their assumption of the cross-dimensional commonality/association, different accounts hold different views on the mechanics of cross-dimensional interactions.

2. Mechanistic accounts of cross-dimensional magnitude interactions

Most forms of magnitude perception and estimation involve three distinct stages: an encoding or accumulation stage where sensory information is registered and encoded into a mental magnitude (in a certain cognitive representational/neural format), a memory stage where the mental magnitude is maintained in and eventually retrieved from working memory, and a response stage where the retrieved mental magnitude is judged against some other magnitude (e.g., to make a reproduction or a comparison). For instance, in a duration reproduction task, subjective time accumulates as the stimulus duration unfolds; then the accumulated time is stored in working memory and later retrieved as the reference for deciding whether an ongoing reproduced duration is subjectively equal to a memorised duration so that reproduction can be terminated (for models of time reproduction, see Riemer, Trojan, Kleinböhl, & Hölzl, 2012; Wackermann & Ehm, 2006; Wearden, 2003). In the case where a stimulus has concurrent magnitudes in different dimensions to be perceived and later judged, the magnitudes are simultaneously encoded and then concurrently held in working memory, and often similarly judged (e.g., reproduced or compared to a reference magnitude). Thus, cross-dimensional magnitude interactions may arise in any of the three stages. Indeed, each of the three stages has been proposed as the locus of cross-dimensional interactions.

It has been proposed that different dimensional magnitudes are encoded using the same mechanism. An early example of such an account is Meck and Church (1983; see also Meck, Church, & Gibbon, 1985), who proposed that a common "counting" mechanism is responsible for encoding both duration and numerosity (see Allman, Pelphrey, & Meck, 2012, for a recent review of this proposal). Walsh (2003) further proposed "a theory of magnitudes" (ATOM), arguing that all dimensional magnitudes are gauged using a common metric and translated into dimension-independent representations of quantities, or mental magnitudes (see also Bonn & Cantlon, 2017; Martin, Wiener, & van Wassenhove, 2017; Lourenco &

Longo, 2010; see Lourenco & Longo, 2011, for a review). Support for this account comes for both behavioural studies showing cross-dimensional interactions (e.g., Lambrechts, Walsh, van Wassenhove, 2013; Lourenco, Ayzenberg, & Lyu, 2016) and neural imaging studies showing overlapping activation in the intraparietal sulcus when different dimensional magnitudes are processed (see Bueti & Walsh, 2009, for a review).

An alternative conceptualisation is that magnitude information is encoded independently by dimension-specific processes but the encoded magnitudes can create interference across dimensions whilst being concurrently held in memory (e.g., Agrillo, Ranpura, & Butterworth, 2010; Cai & Connell, 2015, 2016; Cappelletti, Freemana, & Cipolotti, 2009; Dormal, Andres, Pesenti, 2008; Rammsayer & Verner, 2015). Memory interference is possible if one assumes that magnitudes across dimensions are stored as noisy memories of the same representational format (e.g., mental magnitudes; Gallistel & Gelman, 1992, 2000; Whalen, Gallistel, & Gelmanet, 1999). Under this view, noisy mental magnitudes can be nudged by each other, thus resulting in cross-dimensional interference (Cai & Connell, 2015, 2016). Of course, this account does not necessarily require a common representational format for different dimensional magnitudes; it is possible, for instance, that different dimensions may be structurally correlated (e.g., Lakens, 2012), thus allowing for cross-dimensional interference.

Finally, it is also possible that cross-dimensional interactions arise at the response stage where the response for one dimension is biased by a potential response for another dimension (Moon, Fincham, Betts, & Anderson, 2015; Nicholls, Lew, Loetscher, & Yates, 2011; Yates, Loetscher, & Nicholls, 2012). Yates and colleagues suggested that, when the same “more/less” categorical judgement is required for concurrent dimensions, a response for the target dimension can be primed by potential judgement for the irrelevant dimension (e.g., a line that is longer in length will prime a “longer” response toward the line’s duration).

Moon et al. (2015) assumed that spatial and temporal magnitudes of corresponding ranks cue each other (e.g., the second longest length cues the second longest duration) such that a response to a stimulus' duration is influenced by the potential response to a competing duration cued by the length magnitude. It should be noted that, while these response-bias accounts are able to account for cross-dimensional interactions when the task involves categorical judgements, it is hard to see how they can account for space-time interaction in reproduction tasks (as in the experiments reported here), where no categorical responses are needed (for a similar argument see Cai et al., 2013; Rammsayer & Verner, 2014). Indeed, Starr and Brannon (2016) showed that in duration and length reproductions, a concurrent verbal working memory that arguably severely limits people's ability to verbally label length and duration stimuli as "short" or "long" does not impact the space-on-time effect.

Whatever the locus of the interference, a successful mechanistic account of cross-dimensional magnitude interactions needs to also accommodate the findings that magnitude dimensions vary in their susceptibility to interference from other dimensions: while some dimensions such as duration are mostly susceptible to cross-dimensional interference, other dimensions such as length and numerical magnitude seem to be more resistant to such interference (see Dormal & Pesenti, 2013, for a review, and Walsh, 2014, for some discussion). It has often been observed that, when perceiving concurrent numerosity and duration information (e.g., an array of dots presented for a certain duration), people's duration perception is influenced by the concurrent numerosity information, but their numerosity perception is unaffected by concurrent duration information (Brown, 1997; Dormal et al., 2006; Droit-Volet, Clement, & Fayol, 2003). The relationship between space and numerosity is less clear. While Dormal and Pesenti (2013) showed a stronger influence of numerosity on length than the other way round, Hurewitz, Gelman and Schnitzer (2006) showed that spatial size exerts a greater influence on numerosity than vice versa. In addition, though the magnitude of numbers biases the perceived duration of a concurrent time interval (Cai & Wang, 2014; Chang et al., 2011), it is hard to imagine a scenario where a duration biases the perceived magnitude of a concurrent number. Perhaps more intriguing is the relationship between space (length in particular) and time. It been previously observed that space always exerts a greater influence on time than vice versa (Bottini & Casasanto, 2013; Casasanto & Boroditsky, 2008; Casasanto, Fotakopoulou, & Boroditsky, 2010; Magnani, Oliveri, & Frassinetti, 2014; Merritt, Casasanto, & Brannon, 2010). However, a more recent study by Cai and Connell (2015) suggests that space-time interaction is modulated by a variety of perceptual factors such as modality of perception and format of presentation, with time having greater interference on space than the other way around in certain cases (e.g., when length is perceived via touch; see also Wang & Cai, 2017). In this study, we use space-time interaction (the locus of which is currently being debated; see below) as a test case to explore the mechanics of cross-dimensional magnitude interactions; in particular, we test the hypothesis that magnitudes of different dimensions interact with each other as a result of interference when magnitude representations of different dimensions are concurrently held in working memory. On the basis of the experimental results, we then propose a Bayesian inference model to characterise the occurrence of cross-dimensional memory interference.

3. Magnitude interaction between space and time

The interdependencies in perception between the spatial extent (length) and the temporal extent (duration) of a stimulus have long attracted attention from psychologists. In early studies on space-time interdependencies (Cohen, Hansel, & Sylvester, 1953; Helson & King, 1931), three stimuli are presented in sequence (e.g., three light points, A, B, C, one after another, on a wall) to define two spatial-temporal intervals (between points A and B and between points B and C). A spatial interval is perceived as longer if it is concurrently accompanied with a longer temporal interval (the *tau* effect), and a temporal interval is perceived as longer if it is concurrently accompanied with a longer spatial interval (the *kappa* effect). Later research suggests the task leads people to impute uniform motion to the sequential stimuli, hence the interdependencies between space and time (Jones & Huang, 1982).

More recent research showed that length and duration information still interact with each other even when the task does not introduce imputed motion (Binetti et al., 2015; Cai et al., 2013; Casasanto & Boroditsky, 2008; Magnani et al., 2014; Merritt et al., 2010; Starr & Brannon, 2016). Casasanto and Boroditsky (2008), for instance, presented a static line onscreen for a certain duration; after the disappearance of the line, participants reproduced either the duration (by making two mouse clicks so that the temporal interval between two clicks was the same as the stimulus duration) or the length (by clicking on an X and then somewhere to the right so that spatial interval between the two clicks as the same as the length of the line). They found that the reproduced durations increased as a function of the concurrent length. Cai et al. (2013) had participants watch a video in which a singer sang a note while making a non-sweeping gesture dissecting either a long or short spatial interval; they found that participants perceived the singing to last for longer if it was accompanied by a long than a short gesture.

More striking is the observation of space-time asymmetry, which refers to the finding that, while length exerts an effect on duration, duration has no or a much weaker effect on length. Casasanto and Boroditsky (2008) found that participants were insensitive to the line's duration when reproducing its length, though their duration reproduction was biased by concurrent length information. Such asymmetry in space-time interaction was replicated in subsequent studies where space was presented as filled lengths (e.g., presented as a solid line; Magnani et al., 2014; Starr & Brannon, 2016) and was also observed in children. Casasanto et al. (2010) showed that, when asked which animal travelled for a longer length or for a longer time after watching movies of two animals travelling along parallel paths for different lengths or durations, both 4-5-year olds and 9-10-year olds were more susceptible to the irrelevant length information in their duration judgements than they were to the irrelevant duration information in their length judgements (see also Bottini & Casasanto, 2013, for a similar demonstration). Merritt et al. (2010) observed that adults did perceive a line to be longer if the line was presented for a longer duration, but such a time-on-space effect was argued to be smaller than the corresponding space-on-time effect. These findings of space-time asymmetry have been used to support the conceptual metaphor theory (Boroditsky, 2000; Casasanto & Boroditsky, 2008), which stipulates that people metaphorically employ concrete domains of knowledge to provide scaffolding for the understanding of abstract domains of knowledge (for instance, conceptualising the magnitude of a duration in spatial terms, e.g., a long/short time; Lakoff & Johnson, 1999). Such an asymmetry in representational support (i.e. we use space to support our understanding of time more than vice versa) thus leads to the asymmetry in space-time interaction.

More recent research, however, contradicts this account of space-time asymmetry. Cai and Connell (2015) showed that how length and duration interact depends on their relative memory acuity (or memory noise). They pointed out that previous studies showing space-time asymmetry had used visually presented lines, which afford very detailed perception and memory. Indeed, they showed that when length is perceived with a less dominant sense such as touch (hence more memory noise; e.g., Manyam, 1986; Schultz & Petersik, 1994), concurrent length information fails to bias duration perception and length perception is instead influenced by the concurrent duration information. Wang and Cai (2017) further demonstrated that the format in which length is presented also affects how space and time interact. While duration affects length in both a *static* unfilled length (a spatial interval demarcated by two *simultaneous* boundaries, e.g., | |) and a noisier *dynamic* unfilled length (a spatial interval demarcated by two *asynchronous* boundaries), the effect is larger in the latter than in the former. These studies thus demonstrate that space and time can have bilateral interference on each other and that space-time interaction is modulated by memory noise, which varies according to perceptual factors such as perception modality and presentation format.

Little is known with respect to how space-time interaction (and indeed cross-dimensional magnitude interactions in general) arises and how the interaction may be constrained by perceptual/memory factors. ATOM, as we discussed above, offers a representational account of *why* it is possible for space and time to interfere in perception (i.e. due to a common encoding system), but it is yet to provide a mechanistic account of *how* the interaction takes place (though the theory seems to favour an encoding account; see above). A similar lack of mechanistic characterisation also encumbers the conceptual metaphor theory.

In an attempt to unravel the mechanism of space-time interaction, Cai and Connell (2016) examined whether length affects duration by biasing the actual accumulation of a duration, as visual flicker has been shown to do (Ortega & Lopez, 2008). In a duration reproduction task, visual flicker (a static vs flickering dot) or length (a short vs long line) was manipulated either during the encoding (i.e. accumulation) of the stimulus duration (i.e. participants saw a flickering/static dot or a long/short line presented for a duration and then reproduced the duration) or during the reproduction of a matching duration (i.e. participants saw a neutral stimulus presented for a stimulus duration and then saw a flickering/static dot or long/short line while holding down a key to reproduce the duration). As found in Ortega and Lopez (2008), the flickering manipulation (flickering vs. static dot) produced reverse effects depending on the stage of its presentation: compared to a static dot, a flickering dot led to longer duration reproductions when presented during duration encoding but led to shorter duration reproductions when presented during duration reproduction. These results suggest that the flickering dot (relative to the static one) increased the actual accumulation of whichever duration it accompanied. In contrast, the length manipulation only produced an effect when presented concurrently with the stimulus duration but not with the reproduced duration (see Rammsayer & Verner, 2015, for a similar demonstration concerning spatial size and duration). These findings thus suggest that length information does not bias the actual accumulation/encoding of duration (otherwise length should have had an effect when accompanying the reproduced duration).

Though disconfirming an encoding locus of the spatial effect on time perception, the findings in Cai and Connell (2016) are still steps away from showing that space-time interaction arises as a result of memory interference. Critically, their findings do not directly show that it is the memories of the encoded length and duration that interfere with each other. In addition, it is yet unclear how memory interference between space and time can account for the findings that space-time interaction is modulated by perceptual modality and length format (e.g., Cai & Connell, 2015; Homma & Ashida, 2015; Wang & Cai, 2017).

4. The current experiments

In this paper, we address whether space-time interaction has its locus in memory by directly testing whether memories of length and duration bias each other and whether memory interference, if observed, is modulated by the memory noise associated with a magnitude dimension. To do this, we would need an experimental paradigm that would allow for keeping constant at the encoding stage the magnitude of the interfering dimension (e.g., length for a duration reproduction task) while varying in memory the interfering dimension's magnitude; observation of a cross-dimensional interaction as a result of magnitude memory manipulation would constitute evidence for memory interference among different dimensional magnitudes. To achieve this aim, in Experiment 1, participants perceived, for a variable duration, two line segments (in different colours) of complementary lengths (e.g., 100 and 500 pixels, or 200 and 400 pixels) forming a constant-length combined line (see Figure 1). After the disappearance of the lengths, participants received a cue indicating which of the two lengths they were to later reproduce; this allowed for the cued length to be foregrounded in working memory and to influence the memory of the duration, as would be expected if space-time interaction results from memory interference. Then participants reproduced the stimulus duration and finally the cued length. Note that in this paradigm, the length dimension (the two segment lengths and also the combined length of the whole line) was kept constant in encoding; therefore, if duration reproduction is influenced by the magnitude of the cued length, such an effect cannot arise from encoding and should instead be attributed to memory interference. Experimental scripts and materials (together with data analyses) for all the experiments reported in this study can be found on the Open Science Framework (https://osf.io/zrg7d/).

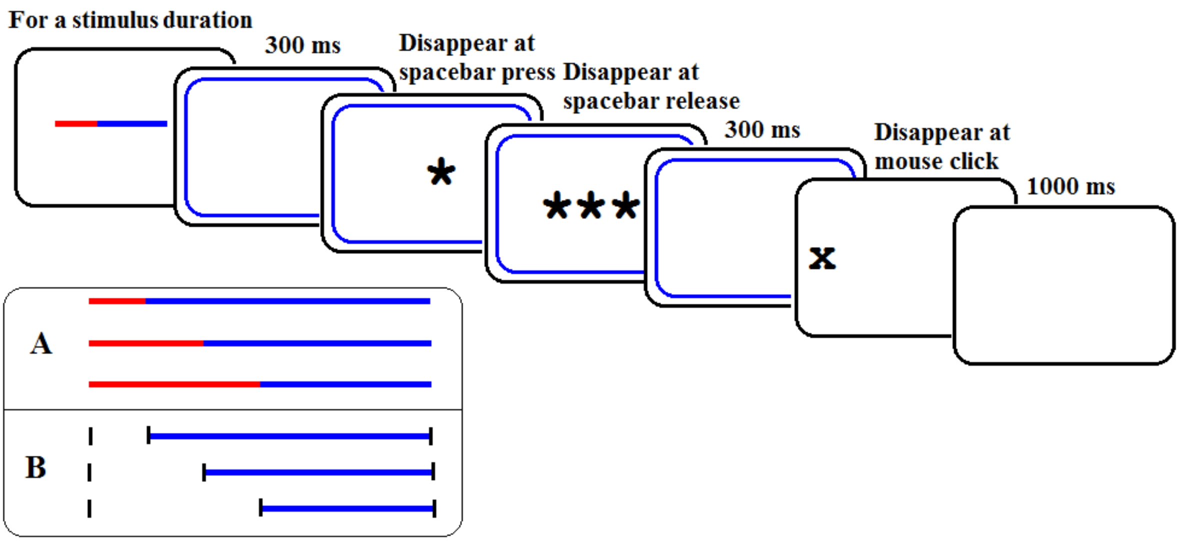

Figure 1. Trial structure for Experiment 1 (and other experiments followed a similar structure; see text for exceptions). Inset presents sample length stimuli (scaled for the figure) for Experiments 1 and 2 (Inset A; filled lengths) and Experiment 3 (Inset B; filled and unfilled lengths).

The rest of paper is organised as follows. First, we show that, in the above paradigm, reproduced durations increase as a function of the cued length if the to-be-reproduced length is cued before the perceived duration is retrieved from memory (i.e. when the to-be-reproduced length is cued *before* duration reproduction; Experiment 1), but not if it is cued after the perceived duration has been retrieved from memory (i.e. when the to-be-reproduced length is cued *after* the start of duration reproduction; Experiment 2). These findings clearly suggest that length biases duration as a result of memory interference when they are concurrently held in memory. Experiment 3 demonstrates that the memory interference effect of space on time occurs when space is presented as less-noisy filled lengths (which afford detailed perception and memories) but *not* when space is presented as noisier unfilled lengths. Experiment 4 further demonstrates that time can also bias space in memory when space is presented as noisy unfilled length. Finally, we propose a Bayesian inference model to account for memory interference among magnitude dimensions and discuss implications for cross-dimension magnitude interactions.

5. Experiment 1

In this first experiment, we investigated whether length biases duration as a result of memory interference. As shown in Figure 1, after seeing two complementary lengths (line segments) forming a constant-length line presented for a variable duration, participants were cued which length they were to later reproduce; then they first reproduced the stimulus duration and finally reproduced the cued length. If space biases time as a result of memory interference, we should expect the duration memory to be biased by the memory of the cued length; hence reproduced durations should increase as a function of the cued length.

5.1. Method

5.1.1. Participants

Twenty-two participants (2 replaced due to poor performance; see below) from South China Normal University took part in the experiment in return for a payment of 10 RBM (about $1.5). All had normal or corrected-to-normal vision, with no reported colour blindness.

5.1.2. Design and materials

The experiment adopted a 5 (cued length: 100, 200, 300, 400 and 500 pixels) x 5 (stimulus duration: 900, 1200, 1500, 1800 and 2100 ms) design. We created 5 red line segments respectively 100, 200, 300, 400 and 500 pixels long and 5 blue line segments of the same lengths. We combined the red and blue segments in such a way that the overall length of the combined line was always 600 pixels long (e.g., 100 pixels in red and 500 pixels in blue; see Figure 1), resulting in 5 length combinations. Pairing the length combinations with the two left/right arrangements of the colours (red-blue vs blue-red) resulted in 10 lines.

These lines were further paired with each of the 5 stimulus durations, resulting in 50 line-duration combinations. Each of these combinations had two versions where either the red or the blue segment was the cued length, thus resulting in a total of 100 trials. For example, in a trial, participants might see a 1200 ms presentation of a line consisting of a 100-pixel red segment on the left and a 500-pixel blue segment one the right, with the blue segment later being cued as the to-be-reproduced length.

5.1.3. Procedure

The experiment was run on E-Prime 1.0 on a 1024 x 768 computer screen. After giving their informed consent, participants were individually tested in a cubicle. They were seated about 60 cm away from the computer screen. Before the main experiment, they underwent a practice session consisting of 8 trials. Each trial began with a line consisting of a red and a blue segment presented for a certain stimulus duration (see Figure 1), which was then replaced by a 300 ms blank screen with a red or blue border, the colour of which served as a cue informing participants about which of the two lengths they were to later reproduce (e.g., a red border informed participants that they were to later reproduce the length of the red segment). All subsequent events in the trial had the same coloured border until the length reproduction event (see Figure 1). After a blank screen of 300 ms, an asterisk appeared at the centre of the screen, after which participants could begin the reproduction of the stimulus duration by holding down the spacebar and terminate the reproduction by releasing the spacebar. The single asterisk, at the press of the spacebar, turned into three, which remained on screen until the spacebar was released. After the release of the spacebar, another blank screen (still with the same colour border) stayed on screen for 300 ms and was then replaced by a screen (without the colour border) with an “X” at a random position on the left hand side of the screen. Participants used the mouse to make a click right to the “X” such that the length interval between the centre of the “X” and the click position was the same as the cued length. The length reproduction task was followed by an inter-trial interval of 1000 ms. The experiment lasted for about 20 minutes.

5.2. Results

The coded data and analysis scripts for this and the following experiments are available at the Open Science Framework: https://osf.io/zrg7d/.

A reproduced duration was calculated as the time (in ms) from the press of the spacebar to its release. A reproduced length was calculated as the difference in the x-coordinates (in pixels) between the centre of the X and the click point. We used the following criteria to identify outlier reproductions and poorly-performing participants in this and all the following experiments: 1) a reproduction less than 1/3 or more than 3 times of the stimulus magnitude (e.g., reproductions of less than 400 ms or more than 3600 ms for a stimulus duration of 1200 ms) were considered as an outlier to be removed, and 2) a participant was judged as poor-performing and thus replaced if more than 1/3 of their reproductions in either duration or length were outliers. Two participants in this experiment were replaced. The outlier trimming for the remaining participants led to a removal of 5.3% of the duration reproductions and 1.5% of the length reproductions.

For the remaining data, we averaged, for each participant, the reproduced durations or lengths for each combination of the cued length and the stimulus duration (e.g., 100 pixels with 900 ms) for linear mixed effects (LME) modelling. Following recent proposals (Bates et al., 2015; Matuschek et al., 2017), we determined the best fitting random effect structure using backward model comparison. We first built a model with stimulus duration and stimulus length (both z-transformed) as fixed effects and also with the maximal random effect structure, i.e. including corresponding random effects for all fixed effects (intercepts and slopes) and allowing all random effects to correlate. We next used backward model comparison to determine whether a random slope (and its correlations with other random effects) significantly contributed to the model fit and should thus be kept in the random effect structure; following Matuschek et al. (2017), we set the significance level at 0.2 rather than 0.05 in order to avoid anti-conservativity.

Figure 2 plots reproduced durations and lengths as a function of stimulus duration and cued length and Table 1 presents the LME results. Reproduced durations increased as a function of stimulus duration, suggesting participants' duration reproductions were highly sensitive to the actual duration a line was presented for. Importantly, reproduced durations also increased as a function of cued length, suggesting that the memory of the perceived duration was influenced by the memory of the cued length. Reproduced lengths increased as a function of cued length, but were not affected by the duration of the line. The latter finding that length perception was unaffected by concurrent temporal information is consistent with findings from previous studies using visually presented lines (e.g., Casasanto & Boroditsky, 2008).

Table 1: LME results for Experiment 1. Regression coefficients (*β*) and their *SE*s are standardized; the intercept stands for the mean across all conditions. The LME model for reproduced durations included a maximal random effect structure and the LME model for reproduced lengths included a random effect structure with a random intercept and random slope of cued length.

Task dimension	Predictor	*β*	*SE*	*t*	*df*	*p*
Reproduced duration	Intercept	1109.5	53.6	20.69	21.0	< .001
	Stimulus duration	234.7	21.8	10.77	21.0	< .001
	Cued length	23.8	6.9	3.45	42.9	.001
Reproduced length	Intercept	271.9	6.6	41.18	21.0	< .001
	Stimulus duration	-0.2	1.2	-0.13	505.0	.895
	Cued length	100.7	5.4	18.77	21.0	< .001

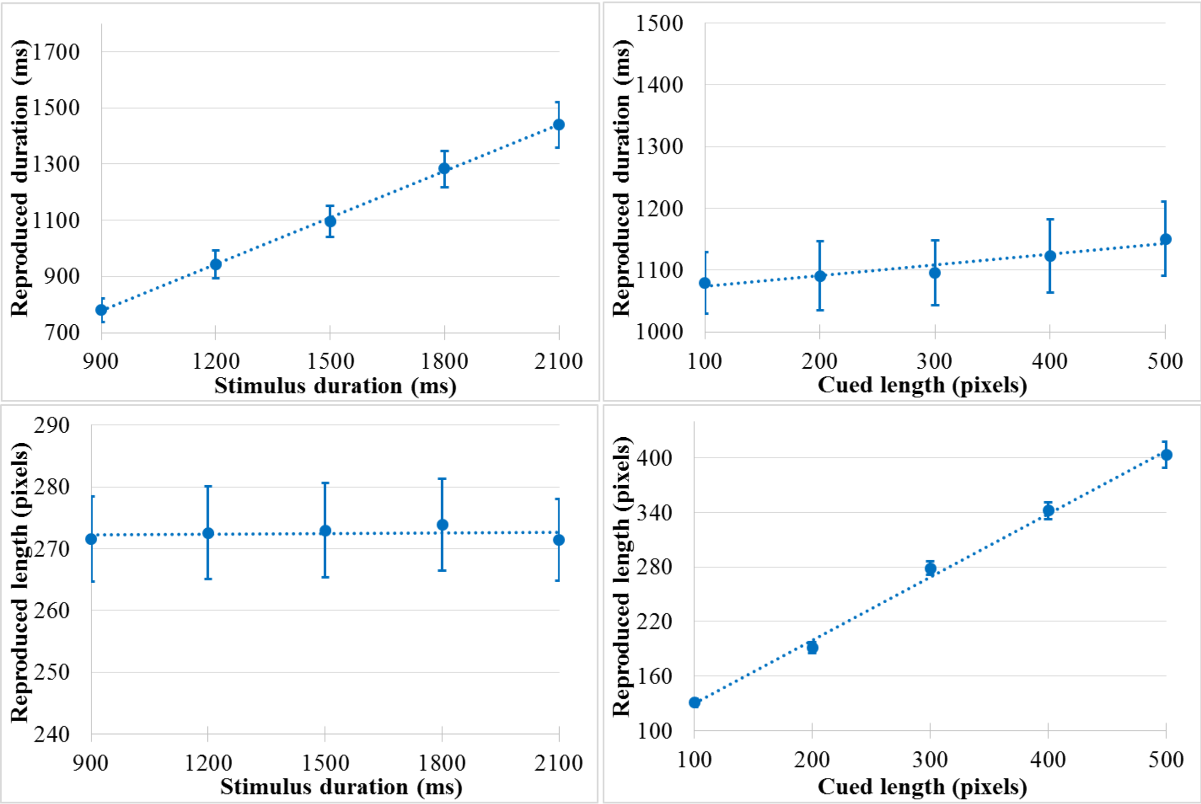

Figure 2. Results of Experiment 1: reproduced durations as a function of stimulus duration and cued length (upper panel) and reproduced lengths as a function of stimulus duration and cued length (bottom panel). Error bars, based on participant means, stand for standard errors.

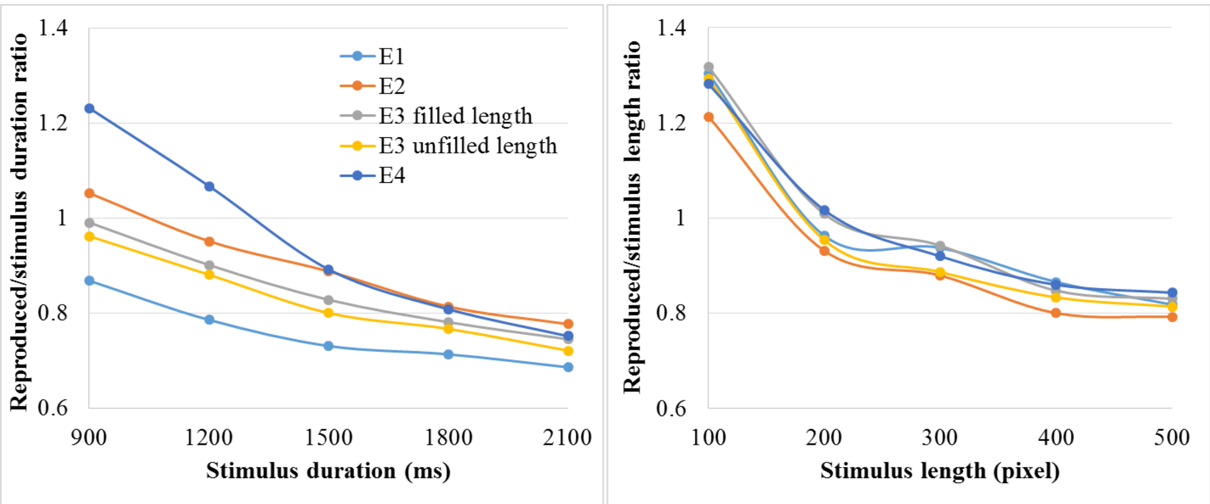

Figure 3. Ratio between reproduced and stimulus duration/length in all experiments.

Finally, we note that, for this experiment and indeed also the following experiments, both durations and lengths appeared to be under-reproduced as a whole; for instance, the intercepts in Table 1 were smaller than the average of the stimulus durations/lengths. Such under-reproductions probably reflect a response bias where people tend to arrive at a premature equivalence when estimating a being-reproduced duration (and indeed also other accumulating magnitudes; see Riemer et al., 2012). In addition, there is regression to the mean in both duration and length reproductions in this and also other experiments (see Figure 3), that is, small magnitudes were relatively over-reproduced while large magnitudes were relatively under-reproduced (for reviews see Gu & Meck, 2011; van Rijn, 2016). Such a regression-to-the-mean bias has been argued to have resulted from Bayesian inference in magnitude estimation (e.g., Jazayeri & Shadlen, 2010; Petzschner, Glassauer, & Stephan 2015), an issue we will return to later.

5.3. Discussion

In this experiment, participants first saw two complementary lengths forming a constant-length line presented for a variable stimulus duration, were cued about which of the two lengths to later reproduce. They first reproduced the stimulus duration, and then reproduced the cued length. To do this, participants needed to first encode the duration and the two lengths and then hold them in memory. When a cue was given, they then accessed the memory of the cued length and foregrounded it in concurrence with the memory of the stimulus duration, making it possible for the two dimensional magnitudes to interfere with each other in memory. In this paradigm, the effect of the cued length could *not* have arisen from the duration encoding as the cued length had not yet been designated while the stimulus duration was being accumulated. The observation that the reproduced durations increased as a function of the cued length is the first direct evidence that space-time interaction occurs as a result of cross-dimensional memory interference. In Experiment 2, we tested whether the interference still remains when the cue of the to-be-reproduced length is presented *after* the start of the duration reproduction (i.e. when the duration memory has been retrieved) such that there is no opportunity for the memory of the cued length to bias the memory of the duration.

6. Experiment 2

6.1. Method

This was the same as in Experiment 1 except that the colour border (as a cue for the to-be-reproduced length) was presented *after* the start of the duration reproduction (see Figure 1). Another 20 participants from the same population as those in Experiment 1 took part and was rewarded with 10 RMB; none of them had taken part in Experiment 1.

6.2. Results

The same trimming method of Experiment 1 led to the exclusion of 2.3% of the reproduced durations and 2.2% of the reproduced lengths. Reproduced durations increased as a function of stimulus duration, but, unlike in Experiment 1, they were unaffected by cued length. Reproduced lengths increased as a function of cued length, and, as in Experiment 1, they were free from the interference of stimulus duration (see Table 2 and Figure 4).

To further test whether there is a difference in the effect of cued length on duration reproductions between Experiment 1 and 2, we next conducted a between-experiment analysis, adding experiment (contrast-coded: Experiment 1 = 0.5, Experiment 2 = -0.5) and its interaction with cued length as additional fixed effects; the model included a maximal random effect structure. Reproduced durations increased as a function of stimulus duration (β = 235.7, SE = 14.7, $t(41.0)$ = 16.05, p < .001) and cued length (β = 13.0, SE = 5.0, $t(124.3)$ = 2.58, p = .011), and were shorter in Experiment 1 than Experiment 2 (β = -182.3, SE = 72.4,

$t(40.0) = -2.52$, $p = .016$). More critically, the effect of cued length was moderated by experiment ($\beta = 21.9$, $SE = 9.4$, $t(655.5) = 2.33$, $p = .020$). In light of the results reported in Experiments 1 and 2, such an interaction suggests a cued length affected duration perception only when the cue was presented before the start of duration reproduction (i.e. while the perceived duration is still being kept in memory; Experiment 1) but not after the start of duration reproduction (i.e. after the duration memory has been retrieved for reproduction; Experiment 2).

Table 2: LME results for Experiment 2. Regression coefficients (β) and their *SE*s are standardized; the intercept stands for the mean across all conditions. The LME model for reproduced durations included a maximal random effect structure and the LME model for reproduced lengths included a random effect structure with a random intercept and slope of cued length.

Task dimension	Predictor	β	*SE*	*t*	*df*	*p*
Reproduced duration	Intercept	1296.5	79.9	16.22	19.0	< .001
	Stimulus duration	237.1	20.0	11.84	19.0	< .001
	Cued length	2.2	7.2	0.31	459.4	.760
Reproduced length	Intercept	257.5	8.1	31.61	19.0	< .001
	Stimulus duration	1.7	1.1	1.53	459.0	.128
	Cued length	96.3	4.8	20.0	19.0	< .001

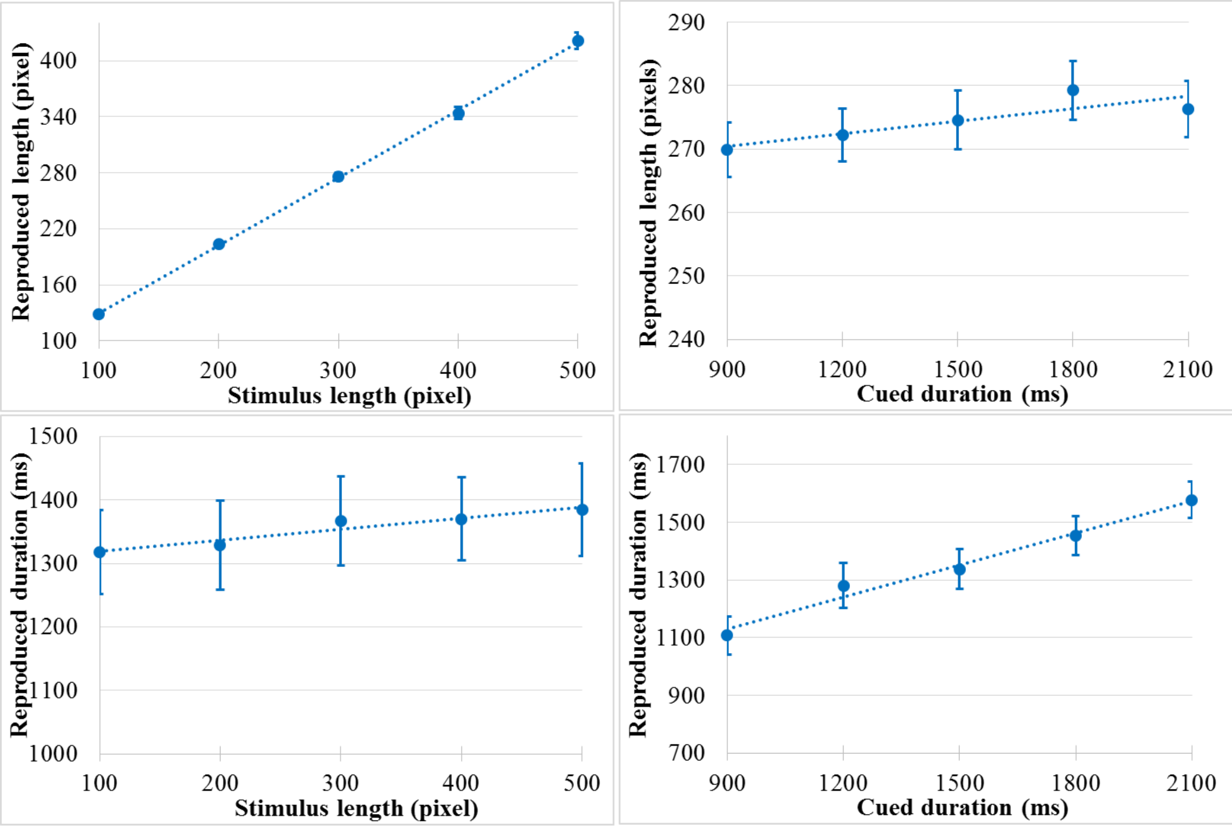

Figure 4. Results of Experiment 2: reproduced durations as a function of stimulus duration and cued length (upper panel) and reproduced lengths as a function of stimulus duration and cued length (bottom panel). Error bars, based on participant means, stand for standard errors.

6.3. Discussion

Though reproduced durations increased as a function of the magnitude of a to-be-reproduced length that was cued before duration reproduction (Experiment 1), such interference disappeared when the to-be-reproduced length was cued at the start of duration reproduction, as confirmed in both individual and cross-experiment analyses. The lack of a cued length effect in this experiment was not due to inattention to the cue presented at duration reproduction as participants needed to attend to the cue in order to later reproduce the cued length; in fact, the finding that reproduced lengths neatly increased as a function of the cued length suggests that participants did pay close attention to the cue. Thus, the finding in this experiment clearly rules out the possibilities that the cued length affects duration accumulation (otherwise a longer cued length would lead to a shorter reproduced duration) or that different cued lengths are implicitly labelled in a way that systematically biases duration reproduction decisions (see Cai & Connell, 2016, for a similar conclusion). The findings in this experiment and Experiment 1 thus suggest that space-time interaction arises as a result of memory interference. When the length cue was presented before duration reproduction, memory of the cued length was foregrounded in concurrence with the memory of the stimulus duration, giving rise to cross-dimensional memory interference. However, when the cue was presented during duration reproduction, the memory of the stimulus duration had been retrieved for duration reproduction (e.g., Treisman, 1963; Gibbon et al., 1984; Wearden, 2003), hence not susceptible to the interference of the cued length. We will later return to the mechanism underlying such cross-dimensional memory interference.

7. Experiment 3

The first two experiments showed that the space-on-time effect arises as a result of memory interference, but how can such an account accommodate findings that space-time interaction is modulated by the modality and format in which spatial length is perceived? As discussed earlier, when space is presented visually as filled length, it biases reproduced time but itself is not biased by time (e.g., Casasanto & Boroditsky, 2008); in contrast, when space is haptically perceived, it is susceptible to interference from time (Cai & Connell, 2015). Wang and Cai (2017) also showed that space-time interaction hinges on length format: while filled lengths (e.g., in the form of a solid line) unilaterally affect concurrent durations, unfilled lengths (e.g., demarcated empty spatial intervals) and concurrent durations have a reciprocal influence on each other. They further showed that these different patterns of interaction are due to the fact that unfilled lengths afford noisier memory representations than filled lengths; hence, unfilled lengths are more susceptible to temporal interference than filled lengths.

In this experiment, we tested whether the memory interference effect of space on time differs for filled and unfilled lengths. We first carried out a pretest, where we assessed whether filled lengths are associated with less memory noise than unfilled lengths. To do this, we examined the coefficient of variation (CV for short, calculated as the ratio between the standard deviation and the mean of reproductions), which has been used to measure the memory noise of mental magnitudes (Cicchini et al., 2012; Droit-Volet, Clément, & Fayol, 2008; Halberda, 2011; Schulze-Bonsel et al., 2006; Wearden, Denovan, Fakhri, & Haworth, 1997): a larger CV signals more noise associated with a mental magnitude. Then in the main experiment, we examined whether filled and unfilled lengths exerted differential effects on duration perception. If we show that lengths with a noisier memory affects duration to a lesser extent than lengths with a less noisy memory, then we can conclude that memory noise indeed modulates space-time interaction.

7.1. Method

The main experiment was the same as Experiment 1 except for the following. The red line segment in Experiment 1 was replaced with an unfilled length demarcated by two black vertical bars (see Panel B in the inset in Figure 1). Participants were instructed to reproduce the filled length (i.e. length of the blue segment) if they had seen a blue border or the unfilled length (length of the demarcated empty interval) if they had seen a red border. The pretest was similar to the main experiment except that the line (consisting of a filled and an unfilled length) was always presented for 1.5 seconds and participants only reproduced the cued length (i.e. no duration reproduction task). That is, participants saw a line (e.g., consisting of a 100-pixel filled length and 500-pixel unfilled length) followed by a blue- or red-bordered screen (as the cue for the filled or unfilled length), and then they reproduced the cued length.

The pretest used 50 participants and the main experiment used another 50 participants (6 replaced for poor-performance) who did not take part in the pretest; we increased the number of participants from Experiments 1 and 2 due to the increased complexity of the design and due to the fact that the critical effect was the interaction between cued length and length format. Participants were paid 10 RMB to take part. The pretest lasted for about 15 minutes and the main experiment for about 20 minutes.

7.2. Results

For the pretest, we calculated the ratio (the reproduced length divided by the stimulus length) for each trial and removed any reproduction less than 1/3 or more than 3 times the stimulus length (about 1%). We then calculated the CVs for the two length types for each participant. A paired *t*-test showed that filled lengths resulted in a smaller CV than unfilled lengths (0.20 vs. 0.22, $t(49) = -2.03$, $p = .048$), suggesting that memories of filled lengths were less noisy than those of unfilled lengths.

For the main experiment, we excluded 3.5% of the reproduced durations and 1.2% of the reproduced lengths as a result of data trimming. In the LME model, apart from stimulus duration and cued length, the fixed effects also included length format (filled length = 0.5; unfilled length = -0.5) and the interaction between length format and cued length; the latter critical interaction was to test whether length format modulates the effect of cued length on duration reproduction. Table 3 presents the LME results (see also Figure 5).

Reproduced durations increased as a function of both stimulus duration and marginally so as a function of cued length; they were longer if the cued length was filled than unfilled. Critically, as indicated by the significant interaction between cued length and its format, the space-on-time effect was larger for filled than unfilled cued lengths. To further explore this interaction, we conducted separate analyses for filled and unfilled cued length. When the cued length was filled, reproduced durations increased as a function of both stimulus duration (β = 236.9, *SE* = 14.2, $t(49.0) = 16.65$, $p < .001$) and cued length (β = 27.2, *SE* = 11.6, $t(49.3) = 2.34$, $p = .023$) (in an LME model with a maximal random effect structure). In contrast, when the cued length was unfilled, reproduced durations increased as a function of stimulus duration (β = 228.3, *SE* = 13.2, $t(49.0) = 17.36$, $p < .001$,) but *not* as a function of cued length (β = -5.8, *SE* = 6.7, $t(49.2) = -0.87$, $p = .389$) (in an LME model with a maximal random effect structure). These findings first of all replicate the observation in Experiment 1 that the memory of a filled length biased the memory of a perceived duration; more importantly, they also show that the memory interference effect of space was modulated by length format (and indeed memory noise): it occurred for less noisy filled but not for noisier unfilled length.

Reproduced lengths increased as a function of cued length and were longer with filled than unfilled cued length; they did not significantly change as a function of stimulus duration or the interaction between cued length and its format. Separate analyses showed that, reproductions of filled lengths increased as a function of cued length (β = 99.6, *SE* = 2.7, $t(49.0) = 37.47$, $p < .001$) but not as a function of stimulus duration (β = 0.7, *SE* = 1.0, $t(1148.2) = 0.73$, $p = .469$) (in an LME model with a random intercept and slope of cued length); reproductions of unfilled lengths increased as a function of cued length (β = 98.7, *SE* = 2.7, $t(49.0) = 35.92$, $p < .001$) and also marginally so as a function of stimulus duration (β = 1.8, *SE* = 1.0, $t(1149.1) = 1.85$, $p = .065$) (in an LME model with a random intercept and slope of cued length).

Table 3: LME results for Experiment 3. Regression coefficients (β) and their *SE*s are standardized; the intercept stands for the mean across all conditions. The LME model for reproduced durations included a maximal random effect structure and the LME model for reproduced lengths included a random effect structure with a random intercept and random slope of cued length and length format.

Task dimension	Predictor	β	*SE*	*t*	*df*	*p*
Reproduced duration	Intercept	1220.3	37.9	32.20	49.0	< .001
	Stimulus duration	232.5	12.7	18.29	49.0	< .001
	Cued length	10.7	5.5	1.95	60.6	.056
	Length format	16.8	5.9	2.85	49.2	.006
	Cued length: Length format	16.5	7.7	2.14	49.4	.037
Reproduced length	Intercept	269.6	4.5	59.79	49.0	< .001
	Stimulus duration	1.2	0.7	1.83	2347.2	.068
	Cued length	99.1	2.6	38.10	49.0	< .001
	Length format	4.39	0.9	5.12	48.9	< .001
	Cued length: Length format	-0.5	0.7	-0.79	2347.2	.427

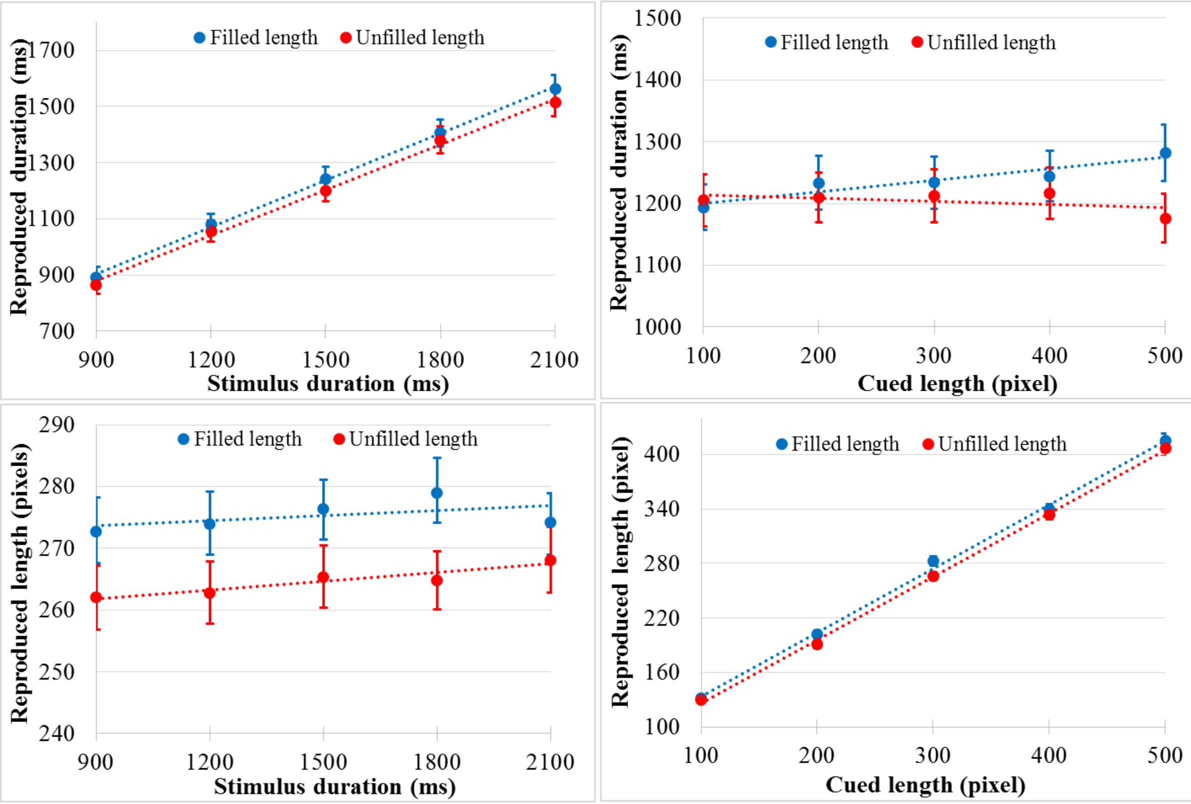

Figure 5. Results of Experiment 3: reproduced durations as a function of stimulus duration, cued length and length format (upper panel) and reproduced lengths as a function of stimulus duration, cued length and length format (bottom panel). Error bars, based on participant means, stand for standard errors.

7.3. Discussion

The finding that reproduced lengths were longer for filled than unfilled cued lengths is consistent with previous research (Pressey & Moro, 1971). More importantly, results from CV showed that filled lengths afford less noisy memories than unfilled length. This difference in memory noise critically relates to the finding that filled and unfilled have differential effects on duration reproductions: the less noisy memory of the filled length biased the concurrent duration memory, replicating the finding in Experiment 1; however, noisier unfilled lengths failed to affect duration reproductions. Such a finding is consistent with the conclusion of Cai and Connell (2015) that the interaction between space and time is shaped by the acuity with which space is perceived and memorized. Indeed, in another study (Wang & Cai, 2017), we provided additional evidence that the amount of interference a dimension is susceptible to is proportionally related to the memory noise of that dimension (a point we will return to in the general discussion).

While we argued that the difference in memory noise between filled and unfilled lengths led to differences in the effects of these two length types on duration perception, it is important to note that we cannot rule out the possibility that some other difference between the two length formats led to the observed results as we manipulated memory noise through stimulus format. For instance, it is possible that filled lengths are more accessible during encoding than unfilled ones, hence their differential effects in cross-dimensional interactions (e.g., Bottini & Casasanto, 2013; Homma & Ashida, 2015). However, this alternative explanation is unlikely for two reasons. First, as we discussed before, there is evidence that space-time interaction does not arise during the encoding stage (Cai & Connell, 2016; Rammsayer & Verner, 2015; see also Experiment 2); therefore, it is unlikely that accessibility alone can modulate space-time interaction. A more likely mechanism is that more accessible lengths (e.g., filled lengths compared to unfilled lengths) result in less noisy memories; hence they exert a greater influence on concurrent duration memories, which is exactly the account we proposed (we will return to the causes of memory noise later). Second, and more critically, Wang and Cai (2017) reported evidence that cross-dimensional interaction is indeed modulated by memory noise associated with interacting magnitude dimensions. They first measured each participant's memory noise in duration and length perception using unidimensional pretests (one for duration reproduction and one for length reproduction) and then measured that participant's susceptibility to cross-dimensional interference in a space-time experiment (similar to ours). They found that 1) susceptibility to temporal interference in length estimation increased linearly with a participant's length memory noise; 2) susceptibility to spatial interference in duration estimation perception increased linearly with a participant's duration memory noise; and 3) the extent of space-time asymmetry (i.e. the difference between the space-on-time effect and the time-on-space effect) increased linearly with the difference between a participant's memory noise in time and space. These findings thus provide strong independent evidence that it is memory noise that determines how two dimensions interact (while it would have been desirable to conduct a similar analysis correlating a participant's memory noise of different lengths in the pretest with his/her space-on-time effects, as Wang and Cai did, this analysis was not possible here because we had different participants in the pretest and the main experiment). In summary, on both theoretical and empirical grounds, we favour the memory noise account over the accessibility account for the results we observed in Experiment 3.

The current experiment also revealed a marginally significant result showing that duration was able to affect length when length was unfilled (i.e. with relatively a large level of memory noise). This finding is again consistent with Cai and Connell (2015), who observed an effect of time on space when space was perceived with high noise (i.e. haptically). It should be noted that the marginal result might due to the large amount of noise in the length reproduction data as a result of the length reproduction task being a carried out after duration reproduction. In Experiment 4, we specifically tested whether duration information can exert memory interference on length when length is unfilled.

8. Experiment 4

Much research has failed to demonstrate any interference of time on space (e.g., Casasanto & Boroditsky, 2008; Magnani et al., 2014; Starr & Brannon, 2016). Cai and Connell (2015) argued that this was because length in previous studies was memorised with high acuity. Building on the finding in Experiment 3 that space-time interaction is modulated by memory noise, in this experiment, we tested whether time can also bias space in memory when space is presented as noisy unfilled lengths. To do this, we modified the paradigm of Experiment 1 (see Figure 6). An unfilled length demarcated by two vertical bars of a particular colour (e.g., blue) was presented for a variable stimulus duration and then the same unfilled length demarcated by two vertical bars of another colour (e.g., red) at the ends was presented at the same location for another stimulus duration. Participants were informed beforehand that the two unfilled lengths were the same in magnitude but they might be presented for different durations. After the disappearance of the second unfilled length, participants were cued which of the two durations to later reproduce after first reproducing the length. If duration memory can similarly interfere with length memory, we should expect reproduced lengths to increase as a function of cued duration.

8.1. Method

8.1.1. Participants

42 participants (1 replaced due to poor performance) were recruited from the same population as in the previous experiments (none of them had taken part in a previous experiment). We increased the number of participants from Experiment 1 and 2 as the effect of time on space, if any, tends to be small. They were paid 10 RMB for their participation.

8.1.2. Design and materials

The design was similar to that of Experiment 1. We used the usual 5 lengths (100, 200, 300, 400, and 500 pixels) and the usual 5 durations (900, 1200, 1500, 1800, and 2010 ms). Since we presented two durations for each length, we created 5 duration pairs such that the combined duration within each pair was always 3000 ms (e.g., 900 and 2100 ms). Assigning each of the 5 lengths to the 5 duration pairs resulted in 25 length/duration combinations, which were further increased to 50 combinations by counterbalancing the order of the two coloured lengths (i.e. blue-bar length or red-bar length presented first). For each of these 50 combinations, the cued duration (i.e. the duration to be reproduced) was either the first or second duration, resulting in a total of 100 trials in the experiment.

8.1.3. Procedure

The procedure was similar to that in Experiment 1 (but see Figure 6). After giving their informed consent, participants underwent a practice session of 8 trials. A trial began with an unfilled length demarcated by two bars of a particular colour (e.g., blue) and presented for a duration, followed by the same unfilled length demarcated by two bars of a different colour (e.g., red) and presented for another duration. The second length presentation was then followed by a 300 ms blank screen with a colour border (blue or red) as a cue informing participants about which stimulus duration (duration of the blue-bar or red-bar length). The blank screen was followed by the length reproduction task that we used in the previous experiments: participants saw an “X” appearing at a random position on the left of the screen and clicked somewhere to the horizontal right of the “X” such that the length between the “X” and the click point would equal the stimulus length. The length reproduction task was followed by another blank screen of 300 ms with the same colour border as in the first blank screen. Then participants saw an asterisk and held down the spacebar to reproduce the cued duration (according to the colour border previously shown). There was a 1000 ms inter-trial interval. The whole experiment took about 25 minutes to complete.

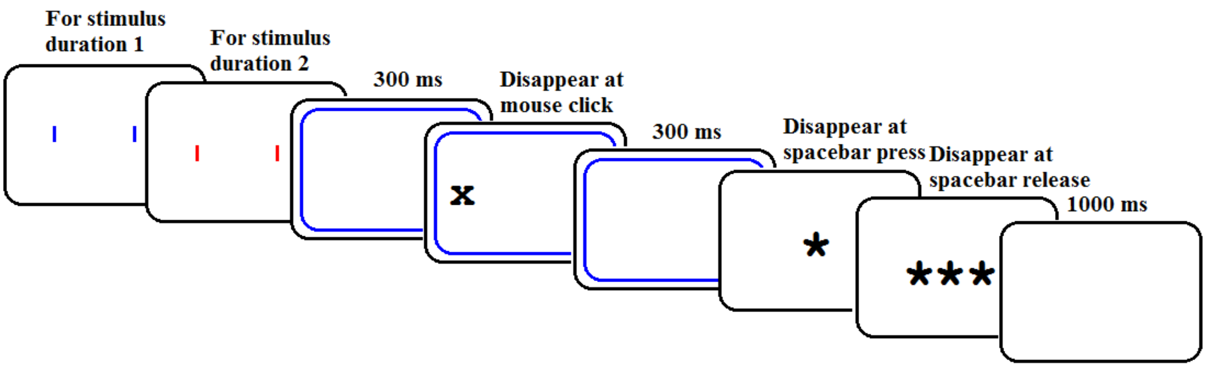

Figure 6. Trial structure for Experiment 4.

8.2. Results

We excluded as outliers 0.2% of the reproduced lengths and 4.2% of the reproduced durations. LME modelling (Table 4) showed that reproduced lengths increased as a function of cued duration as well as of stimulus length (see Figure 7), suggesting an effect of duration memory on length memory. In other words, the time-on-space effect also arises as a result of memory interference, just as the space-on-time effect does. Reproduced durations increased as a function of both cued duration and stimulus length. The effect of stimulus length on duration is consistent with our previous findings of the memory interference effect of length on duration.

Table 4: LME results for Experiment 4. Regression coefficients (*β*) and their *SE*s are standardized; the intercept stands for the mean across all conditions. The LME model for reproduced durations included a maximal random effect structure and the LME model for reproduced lengths included a random effect structure with a random intercept and random slope of cued length (correlation between the random intercept and slope removed due to model non-convergence).

Task dimension	Predictor	*β*	*SE*	*t*	*df*	*p*
Reproduced length	Intercept	274.6	4.2	65.48	41.0	< .001
	Stimulus length	102.9	3.3	30.53	41.0	< .001
	Cued duration	2.8	0.6	4.33	965.0	< .001
Reproduced duration	Intercept	1351.5	66.7	20.27	41.0	< .001
	Stimulus length	22.6	6.9	3.25	41.0	.002
	Cued duration	156.3	14.7	10.65	41.0	< .001

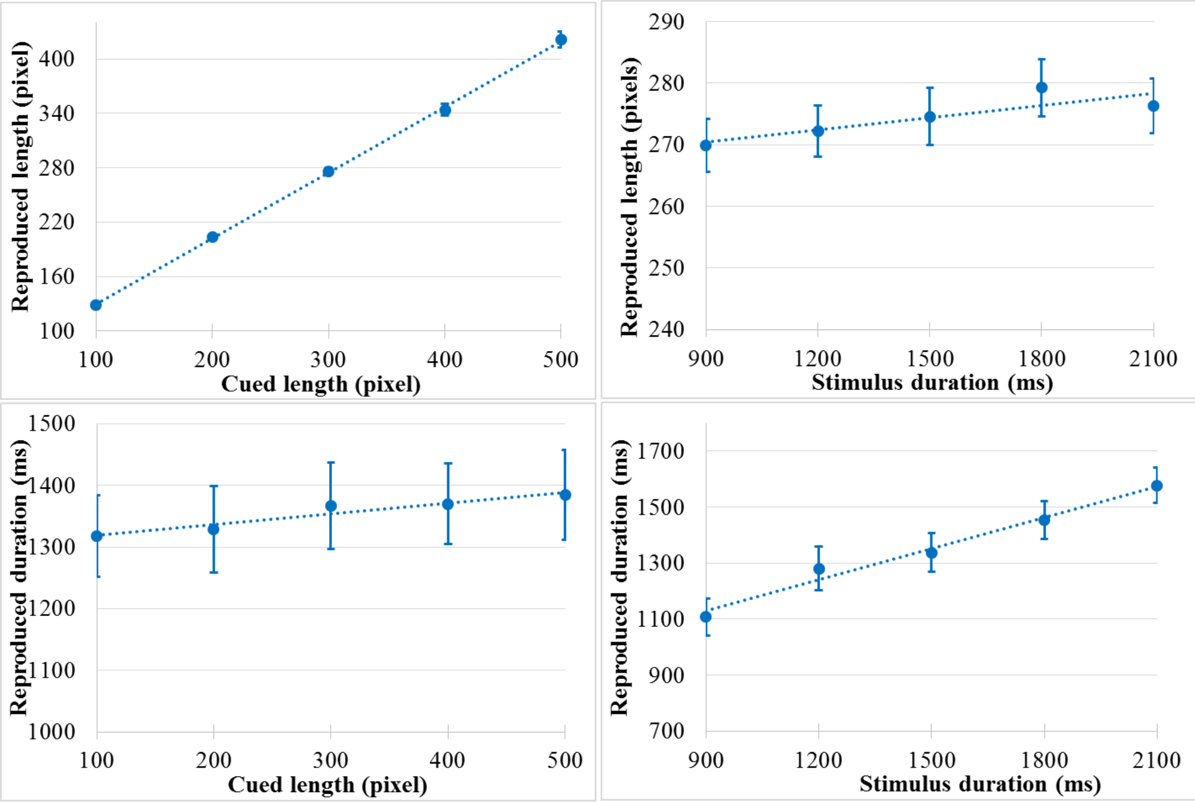

Figure 7. Results of Experiment 4: reproduced lengths as a function of stimulus length and cued duration (upper panel) and reproduced durations as a function of stimulus length and cued duration (bottom panel). Error bars, based on participant means, stand for standard errors.

8.3. Discussion

The finding that reproductions of unfilled lengths increased as a function of cued duration suggests that time can also bias the perception of space so long as space is perceived with a certain amount of memory noise (e.g., unfilled length). This finding is consistent with earlier findings that when space is perceived and memorised with a certain level of noise, space is susceptible to temporal interference (Cai & Connell, 2015; Wang & Cai, 2017). More critically, as the to-be-reproduced duration was cued from memory after the durations and lengths had been encoded, the effect of the cued duration on length reproduction must have arisen as a result of cross-dimensional memory interference.

9. A Bayesian inference model accounting for memory interference in cross-dimensional magnitude interactions

Overall, the experimental findings described thus far provide the first set of direct evidence that cross-dimensional magnitude interactions arise from memory interference. While previous studies indeed have proposed similar hypotheses (Cai & Connell, 2015, 2016; Rammsayer & Verner, 2015), they provided neither direct empirical support nor specific mechanics with regard to how memory interference occurs. For example, Cai and Connell (2015) proposed that memories of magnitude, regardless of their dimensions, may bias each other; however, the mechanics underlying these observations is currently lacking. It is unclear, for instance, how memory interference occurs across dimensions and how it is modulated by memory noise. Here, we propose a Bayesian inference model to explain the mechanics for cross-dimensional magnitude interactions.

Magnitude perception and estimation have been successfully modelled by assuming that these tasks are solved by means of Bayesian inference, whereby a noisy percept is integrated with a prior belief to arrive at a posterior belief about an object's magnitude (e.g., Cheng, Shettleworth, Huttenlocher, & Rieser, 2007; Di Luca & Rhodes, 2016; Griffiths & Tenenbaum, 2011; Huttenlocher, Hedges, & Vevea, 2000; Li & Dudman, 2013; Jazayeri & Shadlen, 2010; Petzschner & Glasauer, 2011; Petzschner, Glasauer, & Stephen, 2015; see Shi et al, 2013, and Van Rijn, 2016, for reviews). Petzchner et al. (2015), for instance, showed that a Bayesian inference model with a prior matching the distribution of experimental stimuli accounts for a wide range of behavioural phenomena (e.g., the regression effect, the range effect, the scalar variability effect, and sequential effects) that are commonly observed in many magnitude dimensions (e.g., length, duration, angle). However, their model is unidimensional and cannot account for cross-dimensional magnitude interactions.

We next present a Bayesian inference model of concurrent magnitude estimation. In Bayesian inference, people form a posterior belief about the magnitude of the target dimension of a stimulus (the estimated magnitude) by integrating a noisy memory of the perceived magnitude of the target dimension with their prior belief about how likely each possible magnitude is for the target dimension. Crucially, we assume that people expect different magnitude dimensions of a stimulus to co-vary in their "amount of stuff". This belief of correlated concurrent magnitudes may have developed from learning about the world, where things larger in one magnitude dimension tend to also be larger in another (e.g., a longer length takes a longer time to travel; Acredolo, 1989; Casasanto & Boroditsky, 2008; Garner, 1976; Piaget, 1969; Smith & Sera, 1992; Stavy & Tirosh, 2000). Thus, in our model, the prior distribution is a correlated multivariate distribution representing beliefs about the likely values of events/objects on all relevant magnitudes. Given the behavioural tendency for people to integrate sensory information across different aspects of a stimulus (e.g., McGurk & MacDonald, 1976; see also Trommershauser, Kording, & Landy, 2011) and the neural basis for such multisensory information integration (e.g., Meredith & Stein, 1986), we further assume that, while magnitudes of different dimensions are separately encoded, the memories of these magnitudes are integrated due to the fact that they are concurrent dimensions of the same stimulus (e.g., the presentation of a line). Empirical evidence for such coupling of magnitudes across dimensions in our experience/knowledge comes from Srinivasan and Carey (2010). In their study, two groups of participants each learned positively correlated pairs of lengths and durations (a longer line was paired with a longer duration) or negatively correlated pairs (a longer line was paired with a shorter duration) and rated familiarity with learned pairs or novel pairs (e.g., negatively correlated pairs for participants initially learning positively correlated pairs). The positive correlation group were able to differentiate learned (positively correlated) length/duration pairs from novel (negatively correlated) pairs, but the negative correlation group could not (i.e. they treated the unlearned positively correlated pairs and learned negatively correlated pairs as similarly familiar). These findings strongly indicate that people have acquired, from their daily experience, knowledge of positive correlation between length and duration that is strong enough to override knowledge from recent contradictory experience.

Thus, when participants are to infer (e.g. reproduce or make a judgement about) the magnitude of a particular dimension, they inevitably recall the memory of the target dimension as well as that of the concurrent dimensions. Integration of these memories is actually optimal as when the different dimensions co-vary in the environment and the memories of the dimensions are noisy, the retrieved magnitude of a concurrent dimension provides useful information about the magnitude of the target dimension. If the dimensions are positively correlated and a concurrent non-target magnitude is perceived to be relatively large, it is likely that the target magnitude is also relatively large. Thus, people can increase their accuracy in estimating the magnitude of the target dimension by relying on noisy memories of both the target and non-target dimensions. The resulting cross-dimensional interference effect is modulated by the relative noise of the memory of the target dimension compared to the non-target dimension. When the noise of the target dimension is low compared to the noise of non-target dimensions (as a result of decreased memory noise of the target dimension or a result of increased memory noise in non-target dimensions), the effect of non-target dimensions will be small. Intuitively, if the memory of the target dimension is already very reliable (i.e. there is little noise, as in the case of a number's magnitude) then the memory of non-target dimensions is not needed when estimating the magnitude of the target dimension. When the noise of the target dimension is high compared to the noise of non-target dimensions, the effect of the latter dimensions will be relatively large. If the memory of the target dimension is unreliable then the memory trace of non-target dimensions provides useful information to reduce the uncertainty about the magnitude of the target dimension (for similar arguments, see also Garner, 1976, and Casasanto & Bottini, 2013).

Before providing a formal description of our model, we illustrate the main aspects of the model as shown in Figure 8. Panel A shows the bivariate prior distribution of two dimensions (shaded region and dotted lines in the margins), as well as a noisy memory of the magnitude of these dimensions (red dot in the shaded region), and the likelihood of this memory (broken lines in the margins). The likelihood of the horizontal dimension is more dispersed (has higher variance) than the likelihood of the vertical dimension, reflecting that the horizontal dimension is relatively noisier compared to the vertical dimension. In addition, the retrieved magnitude of horizontal dimension is relatively large (higher than the prior mean), while the retrieved magnitude of vertical dimension is relatively small (lower than the prior mean). The resulting inferred magnitude on both dimensions (the posterior distribution) is illustrated in Panel B. For both dimensions, the posterior mean lies between the prior mean and the magnitude of the noisy memory, but this regression to the prior mean is relatively larger for the horizontal compared to the vertical dimension. Due to the higher memory noise of the horizontal dimension, the concurrent (vertical) dimension has a larger effect on its inferred magnitude than vice versa. Thus, concurrent magnitude estimation is modulated by memory noise.[1] Panels C and D show the same effect when the retrieved magnitude on both dimensions is relatively large. In this case, regression to the prior mean is less marked than when the retrieved magnitudes are more inconsistent (i.e. the stimulus is relatively large

[1] In general, these effects also depend on the variance of the prior distribution (e.g., the lower the variance of the prior distribution compared to the variance of likelihood, the larger the regression to the prior mean), but for ease of exposition, we have assumed the dimensions are scaled such that they have an equal variance in the prior distribution. We can then interpret the effects more easily in terms of the relative variance of the likelihood (i.e. memory noise) of the dimensions.

according to one dimension, but relatively small according to the other), but the effect is again larger for the relatively noisy (horizontal) dimension.

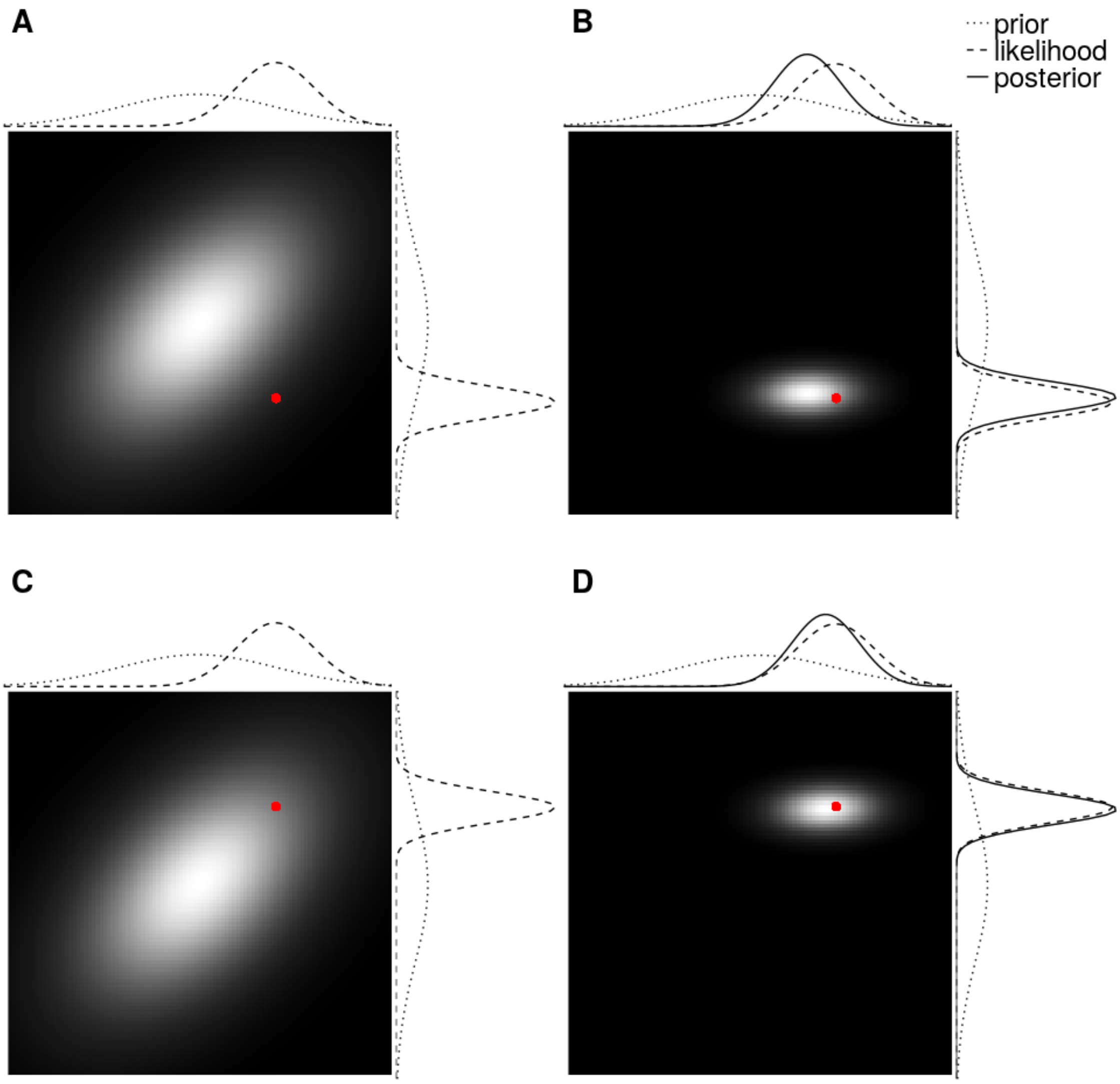

Figure 8. Illustration of the Bayesian inference model of magnitude estimation for concurrent dimensions. (A) The prior distribution (shaded in main panel, where lighter areas reflect more probable magnitudes, and dotted lines in marginal density plots) reflects a belief that the two dimensions are positively correlated. The red dot reflects an unbiased noisy memory signal and broken lines in marginal plots reflect the likelihood, which shows that the horizontal dimension is noisier (more dispersed likelihood) than the vertical dimension. (B) Posterior distribution resulting from integrating the prior and likelihood of Panel A. There is regression

to the prior mean for both dimensions, but this effect is larger for the horizontal (noisier) dimension than for the vertical (less noisy) dimension. (C) Prior distribution as in Panel A, but the memory signal now reflects an object which is relatively large on both dimensions. (D) Posterior distribution resulting from the prior and likelihood of Panel C. Again, there is regression to the prior mean on both dimensions, which is larger for the horizontal (noisier) dimension than for the vertical (less noisy) dimension. Importantly, the regression effect is overall weaker compared to Panel B, where the retrieved magnitudes were less probable according to the prior beliefs.

9.1. Formal description

Let the (column) vector $\boldsymbol{\theta} = (\theta_1, \dots, \theta_d)^\top$ contain the true magnitudes of an object on d dimensions. When asked to estimate the magnitude of the object, a noisy memory signal $\mathbf{x} = (x_1, \dots, x_d)^\top$ is generated. While noisy, the memory signals are assumed to be unbiased, such that on average, they are identical to the true values $\boldsymbol{\theta}$. In particular, we assume the memory signals are drawn from a multivariate Normal distribution, with mean $\boldsymbol{\theta}$ and covariance matrix $\boldsymbol{\Sigma}_\theta$:

$$p(\mathbf{x} \mid \boldsymbol{\theta}) = \mathcal{N}(\boldsymbol{\theta}, \boldsymbol{\Sigma}_\theta).$$

We will refer to $p(\mathbf{x} \mid \boldsymbol{\theta})$ as the likelihood. At time t, someone has a prior belief about the distribution of possible values of $\boldsymbol{\theta}$ represented by a prior distribution. This prior distribution is also assumed to be a multivariate Normal distribution, with mean $\boldsymbol{\mu}_t$ and covariance matrix $\boldsymbol{\Sigma}_t$:

$$p_t(\boldsymbol{\theta}) = \mathcal{N}(\boldsymbol{\mu}_t, \boldsymbol{\Sigma}_t).$$

We further assume that someone estimates an object's magnitude through the posterior distribution

$$\begin{aligned} p_t(\boldsymbol{\theta} \mid \mathbf{x}) &= \frac{p(\mathbf{x} \mid \boldsymbol{\theta}) p_t(\boldsymbol{\theta})}{\int p(\mathbf{x} \mid \boldsymbol{\theta}) p_t(\boldsymbol{\theta}) d\boldsymbol{\theta}} \\ &= \mathcal{N}(\mathbf{m}_t, \mathbf{S}_t) \end{aligned}$$

which is again a multivariate Normal distribution with mean

$$\mathbf{m}_t = \boldsymbol{\Sigma}_t(\boldsymbol{\Sigma}_t + \boldsymbol{\Sigma}_\theta)^{-1}\mathbf{x} + \boldsymbol{\Sigma}_\theta(\boldsymbol{\Sigma}_t + \boldsymbol{\Sigma}_\theta)^{-1}\boldsymbol{\mu}_t,$$

and covariance matrix

$$\mathbf{S}_t = \boldsymbol{\Sigma}_t(\boldsymbol{\Sigma}_t + \boldsymbol{\Sigma}_\theta)^{-1}\boldsymbol{\Sigma}_\theta.$$

Estimates are assumed to equal the posterior mean (which in a Normal distribution equals the posterior median and mode). Note that each posterior mean in $\mathbf{m}_t$ is effectively a weighted average of the values in $\mathbf{x}$ and $\boldsymbol{\mu}_t$. As such, each estimate must lie within the space spanned by these values. Often, an estimate of a dimension j will lie somewhere between the prior mean ($\mu_{t,j}$) and the noisy memory signal (x_j) of that dimension, such that the estimate involves a regression towards the prior mean. However, this is not necessarily the case. For instance, if two dimensions are positively correlated in the prior distribution, the posterior mean of one dimension may be lower than its prior mean, even if the memory signal is higher than the prior mean, when the memory signal of a very reliable nontarget dimension is far below its prior mean (indicative of a relatively low value on that dimension).

In the following, we will illustrate the model for a bivariate signal $\mathbf{x} = (x_1, x_2)$, e.g., duration and length. Considering the case of a single trial, without loss of generality, let the variables be scaled such that the prior distribution has mean $\boldsymbol{\mu}_t = (0{,}0)$ and covariance matrix

$$\boldsymbol{\Sigma}_t = \begin{bmatrix} 1 & \rho \\ \rho & 1 \end{bmatrix}.$$

We will assume the noise in the signal $\mathbf{x}$ is uncorrelated, such that the covariance matrix in the likelihood can be written as

$$\boldsymbol{\Sigma}_\theta = \begin{bmatrix} \sigma^2 & 0 \\ 0 & a\sigma^2 \end{bmatrix}.$$

Here, parameter a reflects the relative noise of the second dimension compared to the first (if $a < 1$, the second dimension is relatively less noisy, while if $a > 1$, the second dimension is relatively more noisy compared to the first). The posterior mean can then be written as

$$\mathbf{m}_t = \begin{bmatrix} \dfrac{(a\sigma^2 - \rho^2 + 1)x_1 + \rho\sigma^2 x_2}{(\sigma^2 + 1)(a\sigma^2 + 1) - \rho^2} \\ \dfrac{\rho a\sigma^2 x_1 + (\sigma^2 - \rho^2 + 1)x_2}{(\sigma^2 + 1)(a\sigma^2 + 1) - \rho^2} \end{bmatrix}.$$

Each posterior mean is effectively a weighted sum of the retrieved magnitude of the first (x_1) and second (x_2) dimension. Defining the relative effect of dimension x_2 on the estimation of dimension 1 as the ratio of these weights, we can derive this relative effect as

$$w_2 = \frac{\rho\sigma^2}{a\sigma^2 - \rho^2 + 1},$$

and similarly the relative effect of x_1 on the estimation of dimension 2 as

$$w_1 = \frac{a\rho\sigma^2}{\sigma^2 - \rho^2 + 1}.$$

We can compare these relative effects by again taking the ratio of them. For $\rho \neq 0$ and $\sigma^2 > 0$, the ratio of these relative effects is

$$\frac{w_2}{w_1} = \frac{1}{a}.$$

From this, it follows that if dimension 1 is more noisy than dimension 2, then dimension 2 exerts a relatively greater influence on the estimate of dimension 1 than vice versa (if $a < 1$, then $\frac{w_2}{w_1} > 1$). This shows how the concurrent magnitude effect is modulated by memory noise (e.g., why filled distance has an influence on duration estimation while duration does not detectably influence distance estimation).

9.2. Evaluation

The Bayesian inference model shows how cross-dimensional interference is modulated by memory noise. Firstly, between two concurrent dimensions, who influences whom in magnitude estimation depends on their relative memory noise: the smaller the memory noise of the concurrent non-target dimension compared to the memory noise of the target dimension, the larger the interference effect on the target dimension. This explains why, for instance, visually presented filled length has a robust influence on duration estimation but itself is less reliably influenced by concurrent duration (Casasanto & Boroditsky, 2008; Merritt et al., 2010). Secondly, the memory noise of a dimension also dictates the dimension's ability to interfere with another dimension (less memory noise leads to better ability to interfere) and its susceptibility to interference from another dimension (less memory noise leads to higher susceptibility to interference; see also Cai & Connell, 2015, for the same conclusion).

Indeed, our relatively simple Bayesian inference model accounts for all the main results observed in the current experiments. In Experiment 1, the length cue foregrounds the cued length in memory, together with the perceived duration. As illustrated in Figure 8, to reproduce the duration, a posterior is computed from the correlated space-time priors and the noisy memories of the duration as well as of the cued length, hence leading to an effect of cued length on reproduced durations (the same mechanism accounts for the effect of cued duration on unfilled length reproductions in Experiment 4). The model also accounts for the lack of an effect of cued length on duration reproductions in Experiment 2. In this case, no length has been cued when a posterior is being computed to reproduce the duration. Hence, though both length memories may be accessed in duration memory retrieval, there will not be a consistent effect of the length memories, as the average of the two lengths is constant in Experiment 2. Experiment 3 showed that increasing the memory noise of length both reduces the effect of length on duration (and increases the effect of duration on length, according to Cai & Connell, 2015). This is consistent with the prediction of the model that the effect of the concurrent non-target dimensions on the estimation of the target dimension increases when the noise of the target dimension increases relative to the noise of the non-target dimensions.

It may be argued that, as larger magnitudes are assumed to have a larger memory noise (Gallistel & Gelman, 1992, 2000), the model should predict the interference effect to increase as a function of the target magnitude. For instance, the effect of space should be greater when the stimulus duration is larger. While we agree with this model prediction, we take the caution that such a prediction may not be borne out in our space-time experiments. Firstly, it is likely that in our experiments the range of magnitudes might be too small to reliably detect this effect. Secondly, a larger target dimension may require more cognitive resources for its encoding and memory maintenance, hence leaving fewer resources that can be directed towards the encoding and memory maintenance of the concurrent magnitude, which then will increase its memory noise. For instance, a duration of 3s will require more cognitive effort to encode and memorise than a duration of 1s. Thus, in the case of the 3s duration, the noise associated with the concurrent spatial magnitude increases and the spatial effect decreases, thus cancelling out the increased spatial effect due to larger memory noise associated with the 3s duration. Therefore, while it is true that, theoretically, cross-dimensional interference should be larger for larger target magnitudes, it is likely that we could not reliably observe this effect in our experiments due to the reasons mentioned above.

We have so far focused on concurrent magnitude estimation within a single trial. Inter-trial effects, such as the sequential effects discussed by Petzchner et al. (2015) can also be accounted for by allowing trial-by-trial shifts of the prior mean through a similar mechanism as proposed by Petzchner et al. We will leave such extensions to future work.

10. General discussion

In four experiments, we demonstrated that space-time interaction arises as a result of memory interference between the perceived length and the perceived duration. Such a conclusion is supported by the demonstrations that, after the encoding of length and duration, the magnitude in one dimension that is cued and hence foregrounded in memory biases the perceived magnitude in the other dimension. In Experiment 1, participants perceived two complementary lengths in a constant-length line presented for a stimulus duration. After being cued which of the two lengths to later reproduce, participants first reproduced the stimulus duration and then the cued length. Reproduced durations increased as a function of the cued length (a finding that was further replicated in Experiment 3). These findings suggest that space-time interaction has its locus in memory: the memory of the cued length biases the concurrent duration memory, hence the effect of the cued length on reproduced duration. In Experiment 2, however, the duration memory has been retrieved when the memory of the cued length is accessed (i.e. during duration reproduction), hence the lack of an effect of the cued length on duration reproduction. The conclusion that space-time interaction arises from cross-dimensional memory interference is further confirmed in Experiment 4: reproductions of unfilled lengths also increased as a function of cued duration, suggesting that the memory of a cued duration biases the concurrent memory of the target length. To our best knowledge, these findings are the first direct demonstrations that space-time interaction arises as a result of cross-dimensional memory interference.

The results in Experiment 2 helps to rule out the possibilities that cross-dimensional magnitude interactions arises as a response bias at the decisional stage. For instance, for Experiment 1, it might be argued that participants implicitly labelled a cued length as "long" or "short", which then led them to reproduce for longer or shorter than the true stimulus duration (e.g., Yates et al., 2012; Moon et al., 2015). If this were the case, we should expect people to also implicitly label a cued length when it was cued at the start of the duration reproduction (in Experiment 2), which would then in turn similarly bias reproduction responses. The fact that the cued length effect disappeared in Experiment 2 rules out the response bias account. In addition, it is worth discussing the possibility that interference may *additionally* occur during the encoding stage (e.g., Bueti & Walsh, 2003; Walsh, 2003). According to this possibility, the complementary magnitudes of a particular dimension (lengths in Experiments 1-3 and durations in Experiment 4) both biased the encoding of the other dimension (duration in Experiments 1-3 and length in Experiment 4) and the effects cancelled each other out. For instance, in Experiment 1, the longer length might have relatively increased the accumulation of the stimulus duration but the shorter length might have relatively decreased the accumulation. As the two lengths were complementary, their effects thus cancelled each other out without any apparent influence on the observed reproductions. While our experiments were not designed to test the encoding locus of space-time interactions, such an account has in fact been ruled out by previous findings. For instance, if a participant perceives a stimulus duration (e.g., in the form of a dot) and then perceives a line of different lengths while reproducing the duration, the length of the line does not bias the accumulation of the reproduced duration (Cai & Connell, 2016; Rammsayer & Verner, 2015). Indeed, the finding in Experiment 2 also suggests that the memory of the cued length does not bias the actual accumulation of the reproduced duration.

Finally, Experiment 3 further showed that the memory interference effects between space and time are modulated by memory noise: less noisy memories of filled lengths, but not the noisier memories of unfilled lengths, were able to bias the concurrent memories of durations. The findings are thus in line with recent demonstrations that the interaction between space and time is modulated by perceptual factors such as perception modality and presentation format (Cai & Connell, 2015; Wang & Cai, 2017) and suggest that, if a dimension has higher memory noise, that dimension is more susceptible to cross-dimensional interference and is less able to influence magnitude memories in other dimensions (we will return to this issue later). We acknowledged that it might be possible that filled lengths are more accessible than unfilled lengths and may therefore have a greater effect on duration reproduction. However, as we discussed before, it is unlikely that accessibility modulates space-time interaction when space and time are being encoded; a more likely explanation is that more accessible filled lengths, compared to less accessible unfilled ones, result in less memory noise, hence a greater space-on-time effect for filled than unfilled lengths.

10.1. Cross-dimensional magnitude interactions as a result of Bayesian inference

The above experimental findings support a Bayesian account where estimation of a stimulus' magnitude on a particular dimension draws on information from the stimulus' other dimensions and takes into account the correlation among concurrent dimensions in the real world. Such an account differs from previous conceptualisations of cross-dimensional magnitude interactions in that it does not require a common encoding mechanism (as ATOM does, e.g., Bueti & Walsh, 2009; Walsh, 2003) or a common memory representational format (e.g., Cai & Connell, 2015, 2016) for different magnitude dimensions. Contrary to the prediction of ATOM, recent research has begun to suggest that different magnitudes are encoded in a dimension-specific way, thus casting doubt on the proposal that there is a common processor for different magnitude dimensions (Agrillo et al., 2010; Borghesani et al., in press; Rammsayer & Verner, 2016; Sobel, Puri, Faulkenberry, & Dague, 2016). Indeed, at least for space-time interaction, there is evidence that the interference does not arise at the stage of magnitude accumulation (Cai & Connell, 2016; Rammsayer & Verner, 2014) and our Experiment 2 showed that the memory of the cued length does not bias the accumulation of the reproduced duration. The memory account offered in Cai and Connell (2016) hypothesized a common representational format for length and duration in order to accommodate cross-dimensional interference; there is, however, no explicit mechanism concerning how magnitudes across dimensions interfere with each other in memory. Apart from the assumption of a common representational format (which is not necessary in our current model), this account can indeed be subsumed in our Bayesian model, which provides a formal mechanism for cross-dimensional magnitude interference.

Our model assumes that cross-dimensional interference arises from people's daily experience and belief that different dimensions of the same stimulus tends to co-vary in quantities such that a stimulus that has "more stuff" in one dimension tends to also have "more stuff" in another (see also Srinivasan & Carey, 2010).[2] Such cross-dimensional association has also been exploited in a recent ACT-R-based computational model of space and time interaction proposed by Moon et al., (2015), who assumed that, in the course of an experiment, participants learn the ranks of magnitudes in each dimension and associate magnitudes of the same rank across dimensions (e.g., the second longest length and the second longest duration). However, the two models differ radically in terms of their mechanics. As discussed, Moon et al.'s model places the locus of cross-dimensional interactions at the response stage. For instance, in their experiment, a line varied in its length or duration in 4 magnitudes. Participants were slower at deciding which magnitude category (out of 4) the magnitude of a pre-specified dimension (e.g., length) belonged to when the concurrent length and duration differed in their ranks (e.g., 2nd longest length and 4th longest duration) than when they agreed (e.g., both 2nd longest). They argued that this was because the magnitude of the non-target dimension (e.g., duration) activated the magnitude of the same rank in the target dimension (e.g., length); thus two different response codes were retrieved when the length and duration were of different ranks, leading to slower responses. In contrast, our model predicts that the inferred magnitude for the target dimension should be shifted from the true magnitude to a greater extent when the two magnitudes were of different ranks than when they were of the same rank, hence the behavioural results. Thus, our model can account for their categorical judgement data, though it is unclear whether Moon et al.'s model can simulate reproduction data (as those in our experiments).

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[2] It is possible that the experience of magnitude co-variation might have been genetically coded or neurally entrenched due to evolution (e.g., Walsh, 2003); note that such an account can explain, for instance, that even neonates associate greater spatial lengths with longer durations, despite having very little experience with space-time co-occurrences in the world (we thank an anonymous reviewer for this suggestion).

10.2. The roles of memory noise and prior experience in cross-dimensional magnitude interaction

As we discussed in the introduction, not all dimensions are created equal in cross-dimensional magnitude interactions; some dimensions seem to “bully” others when different dimensions are concurrently perceived. For instance, numerosity seems to have an upper hand over duration (Brown, 1997; Dormal et al., 2006; Droit-Volet et al., 2003) and visually perceived lengths tend to influence durations more than the other way around (Bottini & Casasanto, 2013; Casasanto & Boroditsky, 2008; Casasanto et al., 2010; Magnani et al., 2014; Merritt et al., 2010; Starr & Brannon, 2016), though in some cases it is possible to have durations exerting a greater influence lengths than vice versa (Cai & Connell, 2015). Such cross-dimensional asymmetries arise naturally in our Bayesian inference model, assuming that magnitudes in different dimensions are maintained in memory with different levels of noise. That is, a noisier mental magnitude is less reliable and hence provides less information about the magnitudes of other dimensions, giving it less power to bias the estimation of dimensions. A noisier mental magnitude is instead more susceptible to the interference from mental magnitudes of other dimensions as, according to experience, these dimensions can provide useful information about the noisy target mental magnitude.

Our study and previous studies provided evidence that cross-dimensional magnitude interactions are indeed modulated by memory noise of the concurrent dimensions. Experiment 3 in the current study showed that, as least for space-time interaction, the direction and the extent of cross-dimensional interference is modulated by their relative memory noises: filled lengths, but not noisier unfilled lengths, bias durations in memory. This result is consistent with previous findings concerning the role of memory noise in space-time interaction. Cai and Connell (2015) showed that noisier memories of haptically perceived lengths, but not less noisy memories of visuo-haptically perceived lengths, were biased by concurrent duration magnitude in perception. Wang and Cai (2017) specifically examined the role of memory noise in space-time interaction. They showed that time is able to affect space both when space is perceived as static unfilled lengths (i.e. an empty spatial interval simultaneously demarcated by two boundaries, as in Experiment 4) and when it is perceived as dynamic unfilled length (i.e. an empty spatial interval sequentially demarcated by two boundaries); in addition, the effect is larger for the noisier dynamic unfilled length than for the less noisy static unfilled lengths. More interestingly, they also showed that the space-on-time effect increases as a function of a participant's memory noise in duration perception (as independently measured in a pretest of duration reproduction) and the time-on-space effect increases as a function of a participant's memory noise in length perception (again as independently measured in a pretest of length reproduction). The extent of space-time asymmetry (i.e. the difference between the space-on-time and time-on-space effects) for a particular participant is also proportional to the difference between duration and length memory noise in that participant. The findings from these studies, together with the current finding in Experiment 3, strongly suggest that the extent and direction of cross-dimensional magnitude interaction are modulated by the relative memory noise of the concurrent dimensions.

We conceptualize memory noise as the uncertainty in a magnitude's representation, which accumulates during various cognitive stages such as the encoding, storage and/or maintenance of a magnitude. Thus, while eventually it is the noise in a magnitude representation that determines how the magnitude interacts with other magnitudes in memory, it is important to note that a variety of factors at different processing stages can affect the noisiness of a magnitude representation. At encoding, perceptual accessibility (e.g., stimulus saliency) can affect the amount of memory noise associated with a magnitude (e.g., Bottini & Casasanto, 2013; Homma & Ashida, 2015): people may have a more vivid memory of a stimulus and thus less noisy memory of the stimulus' magnitude (e.g., length). In addition, during memory maintenance, memory decay will also result in an increasing level of memory noise. Thus, dimensions that afford repeated encoding and memory rehearsal will have reduced memory noise compared to dimensions that do not. For instance, if a length is presented for 3 seconds, participants can repeatedly encode the length and rehearse their memory of the length during the presentation. However, the encoding of duration is a different matter: the encoding does not finish until the end of the 3 seconds and thus there is no repeated encoding. In addition, explicit memory rehearsal may not be practical as it would take 3 seconds to rehearse the memory. This would mean that duration suffers from greater memory decay (and hence has a greater degree of memory) than length in general. Of course, how memory decay affects cross-dimensional magnitude interaction is beyond the scope of this paper and still awaits investigation.

As we briefly mentioned above, cognitive resources such as working memory and attention are additional constraints on the memory noise associated with a magnitude. Working memory and attention are necessary for both encoding a magnitude stimulus and maintaining it in memory. For instance, Starr and Brannon (2016) showed that, while the effect of space on time occurred under a verbal working memory load or no working memory load, it disappeared under spatial working memory load (see Connell, Cai, & Holler, 2013, for a similar demonstration between space and pitch). Under our proposed Bayesian model, while the memory noise of (filled) lengths tends to be smaller than that of durations (e.g., Droit-Volet et al., 2008), a concurrent spatial (but not verbal) working memory load will increase the memory noise of lengths, hence reducing or even eliminating the space effect on time.

Processing automaticity may also affect the level of memory noise. It has been suggested that magnitude dimensions may differ in their degree of automaticity during encoding (Dormal & Pesenti, 2013; Moon et al., 2015). Dormal and Pesenti (2013) observed that numerosity is less susceptible to cross-dimensional interference from length and duration while duration is the most susceptible; they argued that the patterns of interaction were due to numerosity enjoying a higher level of automaticity than length, which is in turn accessed more automatically than duration. Moon et al. (2015) also suggested that the processing of length is more automatic and efficient than the processing of duration, hence the asymmetry in interference between the two. A phenomenon related to processing automaticity is subitizing, a rapid process of encoding with little noise in the resultant mental magnitude when the input magnitude is small (e.g., an array of 4 dots; Dehaene & Cohen, 1994). We suspect that subitizable magnitudes have little memory noise and will hence be strongly resistant to cross-dimensional interference.

Apart from memory noise, prior experience of cross-dimensional association can also impact the way different dimensions interact in memory. It is possible that some pairs of dimensions have more strongly correlated priors than others as a result of our daily experience; therefore, it is a likely that a magnitude dimension will have different extents of interaction with other magnitude dimensions. Space, for instance, normally correlates with time and numerosity in our daily experience; for instance, a longer journey normally takes a longer time to travel and a larger space normally implies the inclusion of more things. Space, however, may have a less close relation with brightness or loudness. If this is the case, then we should expect space to interact with time and numerosity more than with brightness and loudness. Relatedly, it is also likely that our prior knowledge about dimensional association is malleable to recent experience. For instance, it may be possible that exposure to negatively correlated length-duration association in an experimental task may attenuate or even reverse space-time interaction (see Casasanto & Bottini, 2014, for an effect of short-term reading experience on the perceived flow of time).

10.3. Is space special for the mental representation of time?

The conceptual metaphor theory concerning temporal knowledge and perception argues that people use spatial experience to support the understanding of time (Boroditsky, 2000; Casasanto & Boroditsky, 2008; Clark, 1973; Gibbs, 2006; Lakoff & Johnson, 1980, 1999). Two observations have been cited in support of such a proposition. Firstly, in many languages, time is often expressed in spatial terms (e.g., *two days before Christmas*; *two minutes long*). Many have argued that these "linguistic loans" from space to time reflect a deeper conceptual dependency of time on space; indeed quite a few studies have shown that our understanding of time varies according to our spatial experience (Boroditsky, 2000; Boroditsky & Ramscar, 2002; de la Fuente, Santiago, Román, Dumitrache, & Casasanto, 2014).

Secondly, space-time asymmetry is also cited as support for the conceptual metaphor theory. Because durations co-opt spatial terms for mental representation but not the other way round, the space-on-time effect should be always greater than the time-on-space effect, as often observed in some earlier studies (Bottini & Casasanto, 2013; Casasato & Boroditsky, 2008; Casasanto et al., 2010; Merritt et al., 2010). However, more recent experimental findings, as we have discussed, have contradicted such a space-time asymmetry prediction. In particular, there has been much evidence showing that time can bias space to a similar or even larger extent than space does time under certain circumstances (i.e. when space is perceived with a high level of memory noise; Cai & Connell, 2015; Wang & Cai, 2017). In fact, early studies on the *tau* effect (a time-on-space effect) and the *kappa* effect (a space-on-time effect) have shown that when length is presented as unfilled, it is as susceptible to temporal interference as time is to spatial interference (see Jones & Huang, 1982, for a review). The tau effect, together with the demonstrations that the space-time asymmetry can be neutralised or even reversed (Cai & Connell, 2015; Experiment 4), suggests that the space-time asymmetry does not reflect time co-opting space for mental representation.

One can argue that space-time asymmetry may also reflect the extent of metaphorical re-use of space to support time, which can depend on the accessibility of the concurrent physical dimensions (e.g., Bottini & Casasanto, 2013). For instance, it is possible that haptic or unfilled lengths were less accessible compared to visual or filled lengths, hence reducing their interference with temporal processing and making these lengths more prone to temporal interference. This accessibility account can be compatible with the observed data and indeed our proposed model in that, as we discussed above, accessibility or saliency factors modulate a magnitude's memory noise; however, it is important to note that while different length formats can differ in accessibility, it is memory noise (albeit partly determined by accessibility in encoding) that directly determines the direction and extent of cross-dimensional interaction.

Our Bayesian inference model offers a more straightforward account of space-time asymmetry. That is, space-time asymmetry does not reflect dependency of time on space in mental representation. Instead, the asymmetry is caused by the fact that space affords less noisy memories when it is visually presented as filled length: visually presented filled length is not only strong in its cross-dimensional influence but also very robust in resisting interference from other dimensions. When space is perceived haptically or as unfilled length, its cross-dimensional interference decreases or even vanishes and space is more susceptible to temporal interference.

10.4. Cognitive penetration in perception

Many studies in the past decades have investigated how low-level perception (e.g., vision) can be susceptible to influences from higher-level cognitive domains such as motivation, emotion and categorization. Perception of spatial lengths, for instance, is shown to be subject to one's motivation and effort, with people judging a destination to be closer if they find the destination more desirable (Alter & Balcetis, 2011) and a target to be farther away if they have thrown a heavier than a lighter ball (Witt, Proffitt, & Epstein, 2004). Colours are perceived to be darker if they are in a negative emotional state (Meier, Robinson, Crawford, & Ahlvers, 2007) and the perceived colour of an object appears to be tinted with that object's typical colour (e.g., yellow for bananas; Hansen et al., 2006). Indeed, as we briefly discussed earlier, cognitive penetration has been argued to underlie some observations of cross-dimensional magnitude interaction (Nicholls, et al., 2011; Yates et al., 2012). More recently, it was suggested that, instead of infiltrating percept encoding, cognitive factors may at most bias post-encoding memory inference when a judgement is made on the basis of a veridical percept encoded independently of higher-level cognitive influences (Firestone & Scholl, 2015, 2016); for instance, people might be more likely to conclude that the target must be far away after experiencing having difficulty in reaching the target with their throws. The conclusion by Firestone and Scholl that cognitive interference arises in memory rather than encoding is consistent with our current findings and our Bayesian account. Indeed, it may be interesting to consider some of the cognitive effects on perception in light of magnitude memory interference. It is possible that magnitude in weight (e.g., weight of a ball) might exert some interference on the magnitude of distance when people estimate the distance of a target after throwing a ball. If this is the case, it may be interesting to see whether the size of these cognitive effects might reflect the relative acuity or noisiness of the precepts of the target and non-target domains (e.g., target distance and ball weight).

11. Summary

We presented the first set of direct evidence that cross-dimensional magnitude interactions arise from memory interference; in addition, these interactions are constrained by the memory noise associated with the dimensions such that a magnitude with more noise is less able to interfere with other magnitudes in memory and is instead more susceptible to interference from others. Cross-dimensional magnitude interference in memory, we argued, arises from Bayesian inference where people combine their prior experience of correlated magnitudes across dimensions and the noisy memory of the target magnitude.

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