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Cross-dimensional magnitude interaction is modulated by representational noise: Evidence
from space-time interaction

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Abstract

Magnitudes along different dimensions (e.g., space and time) tend to interact with each other in perception, with some magnitude dimensions more susceptible to cross-dimensional interference than others. What causes such asymmetries in cross-dimensional magnitude interaction is being debated. The current study investigated whether the representational noise of magnitudes modulates the (a)symmetry in space-time interaction. In three experiments using different formats of length, we showed that dynamic unfilled lengths result in a higher representational noise than either static unfilled length or static filled length. Correspondingly, we observed that the time-on-space effect was larger for dynamic unfilled lengths than for static unfilled length or static filled length (and it did not differ between the latter two). Further correlational analyses showed that the susceptibility of a target dimension to the influence of a concurrent dimension increased as a function of participants' representational noise in the target dimension (e.g., noisier length representations, a larger effect of stimulus duration on length reproduction). In all, our study showed that the representational noise of space and time modulate the way the two dimensions interact. These findings suggest that cross-dimensional magnitude interactions arise as a result of memory interference, with noisier magnitudes being more prone to being nudged by concurrent magnitudes in other dimensions. Such memory interference can be seen as a result of Bayesian inference with correlated priors between magnitude dimensions.

Key words: space-time interaction; magnitude perception; representational noise; sensory format; Bayesian inference

A major cognitive function in our daily life is to keep track of quantities or magnitudes along different physical dimensions. To pick up a rock, for instance, we need to estimate its size and weight so that we can prepare the hand aperture and calculate how much force to use. More often than not, concurrent dimensions of an object or event (e.g., a rock's size and weight, or a journey's length and travel time) tend to co-vary in their magnitudes such that a larger magnitude in one dimension of an object/event implies a proportionally larger magnitude in another. These correlations in magnitude among different physical dimensions in the real world seem to be part of our long-term knowledge that perception co-opts (e.g., Cai, Wang, Shen, & Speekenbrink, 2018; Srinivasan & Carey, 2010). Lab work has demonstrated that magnitude judgement along one dimension of an object/event tends to be biased by magnitude along other dimensions (e.g., Xuan, Zhang, He, & Chen, 2007). Judgement on spatial magnitudes such as length and size is biased by concurrent such as numerosity and numerical magnitudes. People's judgment of the midpoint of a line, for instance, is biased if a line is flanked with two numbers or dot arrays of different magnitudes (de Hevia, Girelli, Vallar, 2006; de Hevia & Spelk, 2009; see also Fischer, 2001); the font-size of a number is also judged to be larger if the number has a larger magnitude (Besner & Coltheart, 1979; Henik & Tzelgov, 1982; Girelli et al., 2000). Numerosity judgement can be also influenced by concurrent spatial magnitudes. An array of dots tends to be judged as more numerous if the dots appear to occupy a larger area (Hurewitz, Gelman, & Schnitzer, 2006) or to form a longer line (Pufall & Shaw, 1972).

Perhaps the most investigated cross-dimensional magnitude interference in the past two decades is the robust susceptibility of temporal judgement (e.g., of durations) to the interference of concurrent magnitudes in non-temporal physical dimensions (e.g., length; in this paper we use the term "length" for its spatial sense, e.g., the length of a line, and we used "duration" to refer to a temporal interval). For instance, Xuan et al. (2007) showed that a

stimulus with a larger magnitude in a non-temporal dimension (e.g., a display with more dots, a square of larger size, a more luminous display, or a larger-magnitude number) tends to be judged to have lasted longer onscreen. Other studies show similar interference, with durations perceived to last longer if they are accompanied by numbers of larger magnitude (Cai & Wang, 2014; Chang, Tzeng, Hung, & Wu, 2011; Oliveri et al., 2008), by arrays of more objects (Dormal, Seron, & Pesenti, 2006; Javadi & Aichelburg, 2012), by stimuli of larger size (Thomas & Cantor, 1975, 1976; DeLong, 1981; Rammsayer & Verner, 2015), by lines/sticks of greater length (Cai, Connell, & Holler, 2013; Cai & Connell, 2016; Cai, et al., 2018; Casasanto & Boroditsky, 2008; Merritt, Brannon, & Casasanto, 2010), to mention a few.

The interactions between duration and non-temporal magnitude dimensions are of additional theoretical interest because, unlike other forms of cross-dimensional magnitude interference, these interactions have, until very recently, appeared to be unilateral: durations are biased by, but are not able to bias, other magnitudes. For instance, while mutual interference has been observed between size and numerical magnitude (Henik & Tzelgov, 1982; Kaufmann et al., 2005; Szucs & Soltesz, 2007) and between length and numerosity (Dormal & Pesenti, 2013), previous research has shown that duration is influenced by, but does not influence, concurrent non-temporal magnitudes such as numerosity (Dormal & Pesenti, 2013; Dormal, Seron, & Pesenti, 2006), number (Droit-Volet, Clément, & Fayol, 2003, 2008) and length (Casasanto & Boroditsky, 2008; Casasanto, Fotakopoulou, & Boroditsky, 2010; Magnani et al., 2014; Starr & Brannon, 2016). While in some cases duration is observed to also influence the estimation of a concurrent dimension such as length, the effect of duration on length is shown to be much smaller than the effect of length on time (Merritt et al., 2010; but see Cai & Connell, 2015, discussed below).

These cross-dimensional asymmetries between duration and other magnitudes thus present a challenge to the hypothesis of a generalised magnitude system that gauges magnitude information regardless of its dimension, which was proposed to account for cross-dimensional magnitude interference (Lorenco et al., 2016; Walsh, 2003; for reviews see Walsh, 2014; Buetti & Walsh, 2009; Lorenco & Longo, 2011). Built on the proposal that all continuous quantities are represented as noisy mental magnitudes (Gallistel & Gelman, 2000), the generalised magnitude system hypothesis stipulates that all physical magnitudes, regardless of their dimensions, are processed by a common neurocognitive mechanism, which converts different dimensional magnitudes into a common dimensionless metric of mental magnitudes that represents “the amount of stuff” (see also Bonn & Cantlon, 2017). The account has received empirical support from behavioural demonstrations that different magnitude dimensions functionally interact with each other in perception (Meck, Church, & Gibbon, 1983; Lorenco & Longo, 2010; Martin et al., 2017; Lambrechts, Walsh, & van Wassenhove, 2013; Riemer, Diersch, Bublatzky, Wolbers, 2016) and from neural imaging findings that different magnitude dimensions recruit overlapping neural substrates (see Buetti & Walsh, 2009, for a review). On this account, a perceived duration is lengthened in the presence of a longer length (relative to a shorter one) because when both the duration and the length are mapped onto the common metric, the greater value of a longer length (relative to a shorter one) can pull on the duration value as a result of interference, resulting in a longer perceived duration. Such an explanation, however, should also predict that duration can similarly interfere with the perception of non-temporal magnitudes, a prediction inconsistent with the demonstrations that time rarely affects the estimation of concurrent length (and other dimensions; e.g., Droit-Volet et al., 2003, 2008). While acknowledging the challenge of cross-dimensional asymmetries to the generalised magnitude system, Walsh (2014) attributed

these asymmetries to some dimensions (such as space compared to time) enjoying more awareness and being mentioned more in language.

While the generalised magnitude system fails to account for the cross-dimensional asymmetries in magnitude interference, other theoretical accounts have proposed alternative conceptualizations for the interaction between duration and other magnitude dimensions. For instance, the conceptual metaphor account proposes that people recruit spatial experience (e.g., length) to support their understanding of durations (e.g., a longer length representing a longer duration) (Bottini & Casasanto, 2013; Casasanto & Boroditsky, 2008; see also Winter, Marghetis, & Matlock, 2015). The account is built on the philosophical claim that people metaphorically reconstruct a more concrete domain (e.g., space) to conceptualize about a more abstract domain (e.g., time, emotion) (Lakoff & Johnson, 1980, 1999). The account has received support from the observations that people tend to use spatial terms to express time in language (e.g., *long/short*, *before/after*; Lakoff & Johnson, 1980, 1999) and indeed to spatially ground the flow of time (Boroditsky, 2000; Boroditsky & Ramscar, 2002; Bottini, Crepaldi, Casasanto, Crollen, & Collignon, 2015). As people are less likely to employ durations to support the understanding of spatial length, the conceptual metaphor account thus predicts that time-on-space effects (i.e., influences of duration on length), if any at all, should always be smaller than space-on-time effects (i.e., influences of length on duration), a prediction that has been supported by some earlier empirical observations (e.g., Casasanto et al., 2010; Merritt et al., 2010).

A recent study by Cai and Connell (2015), however, shows that cross-dimensional asymmetries do not necessarily reflect conceptual dependency of one magnitude dimension (e.g., time) on another (e.g., space), as the conceptual metaphor account suggests; instead, Cai and Connell proposed that the asymmetries can be accommodated within the framework of a shared memory store among magnitude dimensions (Agrillo, Ranpura, & Butterworth,

2010; Cai & Connell, 2016; Cappelletti, Freeman, & Cipolotti, 2009; Dormal, Andres, Pesenti, 2008; Rammsayer & Verner, 2015). In particular, Cai and Connell observed that spatial length in previous studies was always perceived via vision, a dominant sense in human perception (see Spence, 2009, for a review). They demonstrated a reversal of the space-time asymmetry (i.e., with more influence of time on space than the other way around) when space was perceived via haptics (e.g., by pressing fingers against the two ends of a physical stick), a modality that affords less accurate perception of length than vision (Manyam, 1986; Schultz & Petersik, 1994). In their experiments, participants haptically perceived the length of a stick while listening to a tone lasting for a certain duration and then they reproduced either the length of the stick or the duration of the tone. Reproductions of stick lengths increased as a function of tone duration while reproductions of tone durations did not vary as a function of stick length. These findings thus do not support the conceptual metaphor account, which predicts a stronger space-on-time than time-on-space effect regardless the modality of length perception, and instead uphold a shared representation whereby length and duration interact.

Cai and Connell (2015) proposed the way magnitudes interact is modulated by the noise associated with a magnitude representation. Representational noise is based on the idea that magnitudes are mentally stored with a certain variability and uncertainty (e.g., people don't precisely remember a duration of, say, 1329 ms; Gallistel & Gelman, 2000). Thus, a noisier representation means more variability and uncertainty when this representation is to be retrieved or reproduced. Analogues of representational noise have been proposed and used to account for magnitude perception. For instance, in psychophysics, Weber's fraction has been used to gauge the amount of noise in a magnitude representation (Allan, 1979; Grondin, 2010); in Bayesian inference, the width of the likelihood represents the amount of noise in the evidence (e.g., Ernst & Banks, 2002; Petzschner et al., 2015). On the representational noise

account proposed by Cai and Connell (2015), visual length has lower representational noise than duration (e.g., Droit-Volet et al., 2008) and thus dominates the perception of duration. The dominance of length in the interaction decreases or even reverses for haptic length, due to higher representational noise associated with haptics than vision (e.g., Manyam, 1986; Schultz & Petersik, 1994), therefore resulting in more influence from duration to length than the other way round.

The proposition that representational noise in dimensional magnitudes (e.g., length, duration) modulates cross-dimensional magnitude interaction is further elaborated in a Bayesian inference model proposed by Cai et al. (2018). They presented experimental findings showing that cross-dimensional interactions among dimensional (non-symbolic) magnitudes occur not during magnitude encoding (e.g., Meck & Church, 1983; Walsh, 2003) or decision making (Moon, Fincham, Betts, & Anderson, 2015; Nicholls, Lew, Loetscher, & Yates, 2011) but during memory maintenance and retrieval (see also Cai & Connell, 2016). The interference occurs because of cross-dimensional correlation in people's knowledge of the world (e.g., a larger rock tends to be heavier; a longer journey takes longer time to complete) such that a (noisy) mental magnitude of a dimension is biased (increased or decreased) or by a concurrent mental magnitude of a correlated dimension (see also Srinivasan & Carey, 2010). In particular, the Bayesian inference model in Cai et al. (2018) captures the observation that noisier mental magnitudes (e.g., haptic length compared to visual length) are more susceptible to interference from concurrent mental magnitudes and are less influential in nudging them and also accounts for the long-observed asymmetry between (visual) length and time (e.g., Cai & Connell, 2015).

The present study further investigates the hypothesis that noise in mental magnitudes modulates cross-dimensional magnitude interaction by looking at whether different presentational formats of lengths (e.g., filled vs. unfilled lengths, static vs. growing lengths)

have different levels of representational noise and therefore modulate the way space and time interact. In particular, spatial extent can be presented as *filled* length in the form of a line (e.g., —————) or as *unfilled* length as demarcated by two simultaneous boundaries (e.g., |—————|). In addition, both filled and unfilled lengths can be presented *statically* (a line presented at once for filled length or two boundaries presented simultaneously for unfilled length) or *dynamically* (a growing line for filled length or asynchronously presented boundaries to demarcate an unfilled length). Earlier research has shown that magnitudes (e.g., of length and numerosity) are perceived with more representational noise when presented dynamically than statically (e.g., Droit-Volet, Clement, & Fayol, 2008), a result the current study replicates (i.e., noisier representations for *dynamic unfilled* lengths than *static unfilled* or *static filled* lengths). Thus, the current study set out to explore how space-time interaction may vary as a function of presentational format of length and, more specifically, whether the extent of cross-dimensional interference in a participant is related to his/her representational noise in that dimension.

In addition, we also investigated whether we could accommodate cross-dimensional interference at the participant level using the representational noise of individual participants. Schlichting, de Jong, and van Rijn (2018) have shown that, when estimating the magnitude of a target dimension, participants differ greatly in their susceptibility to a concurrent interfering magnitude. However, it is not yet clear whether such cross-participant variability in cross-dimensional interference is a result of variability in representational noise in magnitude dimensions among individual participants. If that is the case, we then should expect a participant with a large representational noise in the target dimension to be more susceptible to cross-dimensional interference.

In Experiment 1, we examined space-time interaction when space is presented as *static unfilled* length (spatial extent demarcated by two simultaneous boundaries; e.g., |—————|

—|). Then we changed the format of length stimuli into *static filled* length (in the form of a line; e.g., —————) in Experiment 2 and *dynamic unfilled* length (i.e., unfilled length demarcated by two asynchronous boundaries) in Experiment 3. Finally, across all the three experiments, we examined how the size of space-time interference changes as function of the presentational format and how it is related to the representational noise in duration and length in an individual participant.

Experiment 1

Methods

Participants. 24 participants (17 females; mean age = 23.8, 18 - 44) were recruited from the University of Plymouth community (two replaced for poor performance; see below) and received course credits or a monetary reward for their participation. All had normal or corrected-to-normal vision.

Design and materials. The experiment used static unfilled lengths (e.g., |————|). It adopted a 5 (stimulus length: 150, 250, 350, 450 and 550 pixels) x 5 (stimulus duration: 1000, 1400, 1800, 2200, 2600 ms) design.¹

General procedure. Participants were tested individually in a quiet cubicle. They sat about 60 cm away from a desktop monitor, where experimental stimuli were presented using E-Prime. The experiment consisted of three tasks: a unidimensional duration task (as a test of duration representational noise), a unidimensional length task (as a test of length representational noise) and a length-duration task. The two unidimensional tasks were

¹ A power analysis (using the "pwr" package in R) on the space-on-time effect in Casasanto and Boroditsky (2008) (with the effect size averaged across experiments) showed that to reach a power of .80 at $\alpha=.05$ with two predictors in a multiple regression design requires a minimum of 6 data cells. The design in this and the following experiments (with 25 data cells) thus clearly exceeds this minimum.

counter lanced in their order (i.e., duration or length task first) across participants and they always preceded the length-duration task. The experiment took about 30 min.

Unidimensional duration task. For this unidimensional task (see also Figure 1), a static unfilled length (constantly 350 pixels long in all trials) was presented for one of the five stimulus durations (see ***Design and materials***) and was then replaced with a mask for 500 ms. Participants then saw an asterisk at the centre of the screen, after which they could hold down the spacebar and released it when the holding duration was subjectively the same as the stimulus duration to be reproduced (an array of three asterisks stayed onscreen for the whole reproduced duration and disappeared at the release of the spacebar; see Figure 1 top right). There were 25 trials (5 stimulus durations each presented 5 times) randomly ordered for each participant. The task was preceded by two practice trials. Note that in this task (and the following unidimensional length task), participants only attended to one dimension (i.e., duration in this task and length in the length task) as the other dimension was constant and indeed irrelevant to the task at hand.

Unidimensional length task. For this unidimensional task (see also Figure 1), one of the five stimulus unfilled lengths (see ***Design and materials***) was presented for 1800 ms. Participants then saw an X displayed at a jittered position on the left-hand side of the screen. They made a mouse click some length away to the right of the X so that the length between the click position and the X was subjectively the same as the presented stimulus length. There were 25 trials (5 stimulus lengths each presented 5 times) randomly ordered for each participant. The task was preceded by two practice trials.

Figure 1. A schematic illustration of the trial structure for the length-duration task in Experiment 1.

Length-duration task. One of the five stimulus unfilled lengths was presented for one of the stimulus durations (e.g., a length of 150 pixels presented for a duration of 1000 ms), followed by mask for 500 ms (see Figure 1). Then, depending on the cue (an asterisk as a cue for duration reproduction or an X as a cue for length reproduction, as in the unidimensional tasks), participants were to either reproduce the stimulus duration or the length, using the same reproduction methods as in the unidimensional tasks. There were three blocks, each containing 50 trials (i.e., 5 durations x 5 lengths x 2 tasks), which were randomly presented for each participant. The task was preceded by 4 practice trials. Note that unlike the unidimensional tasks, participants needed to pay attention to both dimensions (length and duration) as they would not know which dimension to reproduce until the appearance of the cue (an asterisk or an X).

Results and discussion

All experimental data (for this and other experiments) can be publicly accessed on Open Science Framework (<https://osf.io/8pvst/>). As the representational noise tests (the

unidimensional duration/length tasks) were intended for comparing duration and length noise across experiments, we leave these results for later and will for now focus on the result of the length-duration task. Two participants were replaced as their averaged duration reproduction was less than a half of the stimulus duration. Next, we excluded, as outliers, reproductions that were 1/3 or 3 times of the stimulus magnitude in both duration and length reproduction; this resulted in the removal of 42 out of 1800 duration reproductions (2%) and none of the length reproductions. The remaining data were used to calculate the mean (duration or length) reproduction for each stimulus duration/length combination (e.g., 200 pixels and 1400 ms). We carried out two regression analyses, one on mean duration reproductions and the other on the mean length reproductions, using stimulus duration and stimulus length as predictors (simultaneously entered into the model). As can be seen in Table 1 and Figure 2, reproduced durations increased as a function of both stimulus duration and stimulus length; reproduced lengths also increased as a function of both stimulus duration and length.

Table 1. Results of reproduced length and duration each regressed against stimulus duration and stimulus length in Experiments 1-3. Regression coefficients (β) and their standard errors (SEs) are unstandardized; see partial r for comparison of predictors.

Dependent variable	Predictor	β	SE	$t(22)$	p	Partial r
Experiment 1						
Reproduced duration	Stimulus duration	0.614	0.017	35.38	< .001	.991
	Stimulus length	0.305	0.069	4.40	< .001	.684
Reproduced length	Stimulus duration	0.007	0.002	2.88	.009	.523
	Stimulus length	0.738	0.010	75.80	< .001	.998
Experiment 2						
Reproduced duration	Stimulus duration	0.560	0.017	35.85	< .001	.991
	Stimulus length	0.595	0.066	9.01	< .001	.887
Reproduced length	Stimulus duration	0.002	0.003	0.47	.647	.099
	Stimulus length	0.781	0.014	55.86	< .001	.996
Experiment 3						
Reproduced duration	Stimulus duration	0.496	0.018	25.78	< .001	.984
	Stimulus length	0.549	0.073	7.56	< .001	.850
Reproduced length	Stimulus duration	0.044	0.006	7.90	< .001	.860
	Stimulus length	0.829	0.022	37.51	< .001	.992

Figure 2. Reproduced durations and lengths as a function of stimulus duration and stimulus length in Experiment 1 (blue), Experiment 2 (orange) and Experiment 3 (grey). Error bars stand for ± 1 SE (calculated from a by-participant analysis). Inset: scatterplot for each participant's mean reproduced duration/length for the stimulus durations/lengths.

The cross-dimensional effects in duration and length reproduction clearly show that temporal and spatial information affected each other in perception when length was presented as static unfilled length. Such a finding is in contrast with previous findings of a lack of a time-on-space effect when space is presented as filled length (e.g., Casasanto & Boroditsky, 2008). In Experiment 2 and 3, we changed the static unfilled length respectively into static filled length and dynamic unfilled length.

Experiments 2 and 3

Methods

Another 31 participants (25 females; mean age = 24.4, 18 - 46) took part in Experiment 2 and another 31 (23 females; mean age = 24.1, 18 - 40) took part in Experiment 3 (two participants in each experiment were replaced for substantial under-reproductions, using the criterion in Experiment 1); all of the participants came from the same population as those in Experiment 1 and none had participated in Experiment 1. These two experiments adopted the same design (i.e., 5 durations crossed with 5 lengths) and trial procedure (in both the unidimensional tasks and the length-duration task) as in Experiment 1, except for the format of lengths. Experiment 2 used static filled lengths in the form of a solid horizontal line and Experiment 3 used dynamic unfilled lengths demarcated by two asynchronous vertical bars (i.e., a vertical bar appeared for 500 ms, followed by a blank screen for a stimulus

duration, and then followed by another vertical bar appearing for 500 ms to the right of the first bar).

Results and discussion

The same exclusion and trimming methods as in Experiment 1 led to the exclusion as outliers of 122 (5%) of the reproduced durations and 12 (0.5%) of the reproduced lengths in Experiment 2, and of 72 (3%) of the reproduced durations and 44 (2%) of the reproduced lengths in Experiment 3. Regressions (see Table 1) showed that, in Experiment 2 with static filled lengths, reproduced durations increased as a function of both stimulus duration and length, as observed in Experiment 1; however, unlike in Experiment 1, reproduced lengths increased as a function of stimulus length but not as a function of stimulus duration. In Experiment 3 with dynamic unfilled lengths, reproduced durations increased as a function of both stimulus duration and length and reproduced lengths also increased as a function of stimulus duration and length, as observed in Experiment 1.²

Interestingly, while length continued to affect time reproduction when length was presented static filled length, the effect of time on space disappeared. This finding is in line

² It seems that reproduced durations were the longest in Experiment 3 (where the stimulus duration was defined as the time interval between the two bars) and second longest in Experiment 1. It is likely that more attention was needed to process unfilled lengths in both Experiments 3 and 1, leading to longer apparent durations (e.g., Zakay & Block, 1995); in addition, participants might have inadvertently timed the stimulus duration from the onset of the first vertical bar to the offset of the second vertical bar, hence leading to longer apparent duration. It should be noted that these possible confounds changed the intercept (i.e. longer reproductions across all stimulus durations/lengths) but would have little impact on the slopes (e.g., how reproduced durations changed as a function of stimulus length), which the current paper is interested in.

with previous demonstrations of space-time asymmetry in studies using static filled length (e.g., Casasanto & Boroditsky, 2008; Merritt et al., 2010). However, the effect of space reappeared in Experiment 3 with dynamic unfilled lengths. We next conducted combined analyses on the cross-dimensional interference effects (i.e., effects of space-on-time and time-on-space) to compare these effects within each experiment and also to compare individual effect across experiments; then we tested whether the size of these interference effects are related to a participant's representational noise in space and/or time.

The effects of representational noise on space-time interaction

Following previous literature (e.g., Schulze-Bonsel et al., 2006; Cicchini et al., 2012; Droit-Volet et al., 2008; Wearden, Denovan, Fakhri, & Haworth, 1997), we used coefficient of variation (CV) as a measure of representational noise. CV is calculated as the ratio of the standard deviation divided by the mean for a particular set of data. A larger CV suggests a higher level of representational noise. We used data from the unidimensional duration and length tasks (where participants only perceived and reproduced magnitudes in one target dimension) to respectively calculate each participant's CV for duration and length reproductions (i.e., a larger CV signals a larger variability in reproductions; see Figure 3). For duration, an one-way ANOVA on CVs showed no main effect of experiment ($F(2, 83) = 0.03, p = .248$), with no significant difference between Experiments 1 and 2 ($p > .999$, Bonferroni-corrected for multiple comparisons; same below), between Experiments 1 and 3 ($p = .659$) or between Experiments 2 and 3 ($p = .349$). For length, there was a significant main effect of Experiment ($F(2, 83) = 10.73, p < .001$), with larger CVs (i.e., more noise) for dynamic unfilled lengths in Experiment 3 than either for static unfilled lengths in Experiment 1 ($p = .001$) or for static filled lengths in Experiment 2 ($p < .001$), but there was no significant difference between Experiments 1 and 2 ($p > .999$).

Figure 3. Coefficient of variation (CV) for the duration and length noise tests for different length formats. Error bars stand for 1 SE.

Figure 4. Interference effect size (unstandardized coefficients) for the effect of space on time and time on space across the experiments. Error bars stand for 1 SE.

We conducted two tests to examine whether there is any correlation between the representational noise in duration and length and the cross-dimensional interference effects. First, we tested whether the size of the space-on-time effect and that of the time-on-space effect co-varied across the three experiments in a pattern that can be explained by the representational noise variation across the experiments. Second, we tested whether a participant's susceptibility to cross-dimensional interference could be predicted by his/her representational noise in duration and length. To do these, we first calculated the size of the interference effects by regressing, for each participant, reproduced durations (in one simultaneous multiple regression) and reproduced length (in another simultaneous multiple regression) against stimulus duration and stimulus length. We used the unstandardized coefficient of the length predictor on reproduced duration as the measure for the space-on-time effect size and the unstandardized coefficient of the duration predictor on reproduced lengths as the measure of the time-on-space effect size for each participant (here we opted to use unstandardized rather than the standardized coefficient in order to avoid otherwise possible distortion of the data due to z-score transformation, e.g., Barbaree & Mewhort, 1994).

To compare sizes of interference effects among the experiments, we conducted a one-way ANOVA respectively on the space-on-time effect sizes and another on the time-on-space effect sizes (see Figure 4). The space-on-time effect was similar in size across the experiments ($F(2, 83) = 1.98, p = .145$); post-hoc analyses showed no significant difference between Experiments 1 and 2 ($p = .166$, Bonferroni-corrected, same below), between Experiments 1 and 3 ($p = .452$) or between Experiments 2 and 3 ($p > .999$). The time-on-space effect, on the other hand, was different in size across the experiments ($F(2, 83) = 47.01, p < .001$), with a greater effect for in Experiment 3 with dynamic unfilled lengths than in Experiment 1 with static unfilled lengths ($p < .001$) or in Experiment 2 with static filled

lengths ($p < .001$); there was no differences between Experiment 1 and 2 ($p = .665$).³ The variations in the space-on-time effect size mirrors the pattern of duration representational noise across the three experiments and the variation the time-on-space effect size mirrors the pattern length representational noise across the experiments. That is, representational noise in duration did not significantly vary across the experiments and neither did the effect of stimulus length on reproduced durations. In contrast, representational noise in length was higher in Experiment 3 (dynamic unfilled length) than in either Experiment 1 (static unfilled length) or Experiment 2 (static filled lengths) and the same pattern of differences was observed for the effect of stimulus duration on reproduced lengths.

To further test the idea that the interference effect size increases as a function of representational noise of the target dimension, we next regressed each participant's space-on-time effect size against both his/her duration and length representational noise in a simultaneous multiple regression model and also did the same for the time-on-space effect size. A participant's space-on-time effect size increased as a function of his/her representational noise in duration ($\beta = 1.99$, $SE = 0.78$, $t(83) = 2.54$, $p = .013$) but not as a function of his/her representational noise in length ($\beta = -0.82$, $SE = 0.90$, $t(83) = -0.91$, $p = .368$). A participant's time-on-space effect size increased as a function of his/her

³ One might be puzzled by the null difference here given that stimulus duration significantly affected length reproduction in Experiment 2 but not in Experiment 1. Note the effect size being not significantly different between the two experiments simply indicates that the difference in the effect sizes is not large enough to be statistically detectable or meaningful; this finding does not mean that the effect was similarly present or absent in both experiments (i.e., it is still possible that the effect was statistically present in one experiment but not in the other in individual analyses); therefore, the null difference here does not contradict the results from the individual experiments.

representational noise in length ($\beta = 0.08$, $SE = 0.03$, $t(83) = 2.24$, $p = .028$) but not his/her representational noise in duration ($\beta = -0.01$, $SE = 0.03$, $t(83) = -0.34$, $p = .735$). Although the duration representational noise and length representational noise correlated with each other ($r = .43$, $p < .001$), there was no evidence of serious collinearity in these regression analyses (variance inflation factor = 1.23; O'Brien, 2007).

But do the relative influences that space and time have on each other also change as a function of presentational format and indeed as a function of the relative representational noise levels in each participant? To answer these questions, we would need a measure that would allow us to directly compare the space-on-time and the time-on-space effects. Note that the unstandardized coefficients as calculated above would not serve this purpose as the two predictors and the two dependent variables in the above coefficient calculations differed widely in their ranges (e.g., the stimulus duration range was 1000 – 2600 while the stimulus length range was 150 - 550). To solve this, we used standardized coefficients such that both the space-on-time and the time-on-space coefficients (standardized) both represent the z-score change in the dependent variable per 1 z-score change in the predictor. An ANOVA with interference direction (space-on-time vs. time-on-space) as a within-participant variable and Experiment as a between-participant variable revealed a significant effect of interference direction ($F(1, 83) = 15.95$, $p < .001$), of Experiment ($F(1, 83) = 11.14$, $p < .001$) and the interaction between interference direction and Experiment ($F(1, 83) = 4.72$, $p = .011$). Separate t -tests showed that, for Experiment 1 and 2 (where stimulus length had a relatively low level of representational noise), the interference from space to time is larger than the other way round when length had a lower level of representational noise (Experiment 1: ($t(23) = 2.59$, $p = .016$); Experiment 2: ($t(30) = 3.62$, $p = .001$)). In Experiment 3 (where length had a higher representational noise), the effect size was similar between the two interference directions ($t(30) = 0.83$, $p = .415$). To further test the possible relationship

between relative interference size and the relative noise level in duration and length, we also regressed the difference between the space-on-time and the time-on-space standardized coefficients (the former minus the latter) for a participant against the difference between time representational noise and length representational noise (the former minus the latter) and showed a significant relation between the two ($\beta = 0.60$, $SE = 0.25$, $t(83) = 2.42$, $p = .018$). This finding also suggests that the relative influence of space and time on each other depends on the relative representational noise between duration and length in a participant.

These between-experiment comparisons and individual-difference analyses clearly show that the extent to which a dimension is susceptible to cross-dimensional interference critically depends on the dimension's representational noise such that a dimension with a larger representational noise is more prone to interference from other dimensions and that the interference effects a participant exhibited are a function of the relative noise levels he/she has with duration and length.

General discussion

In three experiments, we found that the way space and time interact varies according to the presentational format of length and indeed according to representational noise with which length is perceived. We observed that while stimulus length affects duration reproduction and does so to a similar extent regardless of the length format, the effect of stimulus duration on length reproduction crucially depends on how length is perceived. In particular, we showed that stimulus duration exerts a larger influence on length reproduction when length is perceived with a higher level of representational noise (e.g., as dynamic unfilled length in Experiment 3) compared to when it is perceived with a lower level of representational noise (i.e., as static length in Experiments 1 and 2). Indeed, we also showed that the space-on-time effect is larger than the time-on-space effect in the case of static

unfilled and filled lengths (Experiments 1 and 2) but the two effects were comparable in the case of dynamic unfilled lengths (Experiment 3). In addition, there is also evidence for a relation between a dimension's susceptibility to cross-dimensional interference and its representational noise: if a participant had a higher noise in a dimension, their reproductions in that dimension experienced more interference from a concurrent dimension. To our best knowledge, these findings are the first demonstration that the presentational format of a magnitude dimension impacts the way the dimension interacts with concurrent dimensions in perception such that the extent to which a dimension interferes with other dimensions in perception is modulated by the dimension's representational noise.

Before we draw any theoretical conclusions, it is worth considering some alternative accounts for the cross-dimensional interactions we observed. When the length of a solid line in Experiment 1 was increased/decreased, arguably the covered area by the line is also accordingly increased/decreased (see Leibovich et al., 2018, for a discussion on the correlation on the co-variation of continuous dimensions); thus, the length effect could arguably also be an area effect on duration (e.g., Wehrman et al., 2020; Xuan et al., 2007). Similarly, it is possible that the apparent effect on duration by dynamically unfilled lengths could be attributed to imputed velocity (e.g., velocity of shifting in space from the location of the first bar to that of the second bar; e.g., Storch & Zimmermann, 2019). While these alternative accounts are possible, they are dispreferred on the basis of parsimony. For example, participants in Experiment 1 perceived the length of the empty interval between two vertical bars (i.e., static unfilled length); hence, the length manipulation here would not have a corresponding change in area or velocity in imputed motion. To explain the cross-dimension interference on duration perception in our experiments, the alternative accounts would then need to assume different possible sources (e.g., length as well as area and/or

imputed velocity) of interference on duration perception. Thus, a more parsimonious account is that our results reflect the interaction between space and time.

The findings that the relative effects of space and time on each other vary as a function of their representational noise present a challenge to the initial proposal of the conceptual metaphor account, which assumes that the asymmetry in space-time interaction reflects the need for temporal knowledge and processing to be spatially grounded but not the other way round (Casasanto & Boroditsky, 2008; Lakoff & Johnson, 1980, 1999). In particular, the finding that space and time can have comparable effects on each other (as in Experiment 3) was inconsistent with the account's prediction that space should always exert a greater effect on time than the other way around (e.g., Merritt et al., 2010). Our findings also suggest that earlier demonstrations of asymmetry in interaction between time and visually filled lengths (e.g., Casasanto & Boroditsky, 2008; Merritt et al., 2010) resulted from lower representational noise in length memories than in duration memories rather than a temporal dependency on space. When spatial representational noise increases (e.g. as in the case of dynamic unfilled lengths), time can impact spatial perception to a similar extent as space impacts time perception (see also Cai & Connell, 2015; Kranjec et al., 2019). However, it should be noted that our findings are compatible with a subsequent development of the conceptual metaphor account by Bottini, Guarino, and Casasanto (2013), who proposed that space-time asymmetry may also reflect, apart from conceptual metaphorical re-use, relative accessibility of the physical dimensions. That is, it is likely that time exerts a lesser influence on space than vice versa because temporal memories are less accessible (e.g., less imageable or memorisable) than spatial memories.

Our findings suggest that space-time interactions are determined by representational noise of magnitude dimensions, with noisier dimensions more susceptible to cross-dimensional interference (Cai & Connell, 2015). The findings that representational noise

modulates the interaction between space and time are also consistent with Droit-Volet et al. (2008), who showed that duration has more representational noise than length or numerosity and also tends to be susceptible to interference from length and numerosity but not the other way round. Indeed, Starr and Brannon (2016) showed that, while filled length unilaterally biases durations under no working memory load or under verbal working memory load (i.e., rehearsing digits), the space-on-time effect disappeared under spatial working memory load (i.e., remembering geometric patterns). Presumably, the spatial working memory load disrupted the representations of remembered lengths, thus inflating their representational noise and leading to the attenuation or eradication of the effect of length on duration reproduction.

The current findings can be accommodated by the Bayesian inference model proposed in Cai et al. (2018), according to which cross-dimensional magnitude interactions arise as a result of Bayesian inference while different magnitudes are concurrently held in working memory. In particular, based on the observations that people tend to integrate different sources of sensory information (e.g., McGurk & MacDonald, 1976; for review, see Trommershauser, Kording, & Landy, 2011) and that magnitude dimensions (space and time in particular) tend to co-vary in people's experience and knowledge (Srinivasan & Carey, 2010), Cai et al (2018) proposed that priors for different magnitude dimensions are correlated in people's knowledge of the world. For instance, in the case of space and time, an object with a longer spatial extent is more likely to also have a longer temporal extent (e.g., a longer journey takes a longer time to complete; see Srinivasan & Carey, 2010 for empirical evidence). Magnitude estimation has been shown to follow a Bayesian inference process where people incorporate both the perceived evidence and their prior beliefs to make an optimal estimate of a perceived magnitude (e.g., Jazayeri & Shadlen, 2010; Laming, 1999; Petzschner, Glasauer, & Stephen, 2015; Zimmermann & Cicchini, 2020). In our experiments,

for instance, a longer length, compared to the shorter one, may entail the belief of a longer duration; such a belief, when combined with the perceived stimulus duration, leads to a longer reproduction of the duration.

More importantly, earlier work repeatedly has shown that the reliability of a percept depends on its precision (e.g., representational noise). For instance, it has been shown that, in cross-modal integration of information, whether people rely more on vision or touch is based on the relative perceptual acuity of the two modalities (Ernest & Banks, 2002; Alais & Bur, 2004). Thus, according to Bayesian inference, the direction and extent of cross-dimensional interference is determined (partly) by the noise (i.e., the width of the probability distribution) of the perceived evidence. The noisier the evidence is, the more weight the prior will have for magnitude estimation and hence the larger the interference from a concurrent dimension. This explains why concurrent duration information rarely affects the estimation of visually perceived filled lengths, which afford a low level of representational noise, but can affect the reproduction of lengths when they are perceived with a high level of representational noise, as in the case of asynchronously demarcated unfilled lengths as in Experiment 3, as in the case of haptically perceived lengths in Cai and Connell (2015), or as in the case of lengths under spatial memory interference in Starr and Brannon (2016).

It should be noted that though the Bayesian inference model in Cai et al. (2018) predicts that the effect of space on time should decrease or even disappear when space is perceived with more memory noise (as in the case of unfilled lengths), our experiments did not show a difference in space-on-time effects across different length formats. However, it should be noted that the null finding does not necessarily constitute evidence of absence (e.g., it may result from a lack of experimental power). Indeed, it has been shown in Cai et al. (2018) that, compared to filled lengths, noisier unfilled lengths were less effective at biasing the estimation of concurrent durations. Furthermore, there is evidence that teenagers make

use of temporal information to infer spatial sources of sounds when they cannot view these sources (Amadeo, Campus, & Gori, 2019).

Our findings, together with the above Bayesian inference account, also have implications for cross-dimensional magnitude interactions in general. In particular, they suggest that the way any two magnitude dimensions interact is constrained by the relative representational noise of the interacting dimensions and the prior correlation between the two dimensions. The first constraint implies that not all magnitudes have an equal footing in cross-dimensional interactions: highly noisy dimensions such like duration are likely to be affected by but not be able to affect by other dimensions (for reviews and discussions, see Dormal & Pesenti, 2013, Walsh, 2014; Winter et al., 2015). Of course, a dimension's representational noise also depends on the modality in which the dimension is perceived (e.g., Droit-Volet et al., 2003).

The second constraint implies the possibility that some dimensions may enjoy a closer prior correlation due to experience. For instance, it is possible that time is more correlated with space than with loudness or brightness in people's prior belief. If that's the case, then we should expect more cross-dimensional interaction between time and space and between time and loudness/brightness. Such a hypothesis awaits confirmation. In addition, it also remains a question as to whether short-term training (e.g., in a lab) is able to reverse the prior belief of correlation acquired from experience (e.g., Casasanto & Bonttini, 2013); for instance, it might be possible that participants can be presented with negatively correlation space-time input (e.g., longer lengths combined with shorter durations), leading to a negative magnitude interaction between space and time (e.g., Cai, Wu, & Wang, 2020).

In summary, we showed that representational noise modulates space-time interaction: while less noisy filled length (in the form of a solid length) biases, but is itself not biased by, concurrent duration, dynamic unfilled length and duration have a comparable influence on

each other. In particular, we also showed that the extent to a dimension is biased by an irrelevant dimension positively correlates with the representational noise the target dimension affords: the higher the noise (i.e., the lower in acuity), the more susceptible a dimension is to cross-dimensional interference.

Data statement

The datasets generated during and/or analysed during the current study are publicly available in Open Science Framework (<https://osf.io/8pvsr/>).

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