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Space is Special:
A domain-specific mapping between time and nontemporal magnitude

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Abstract

Across different domains the magnitude of a stimulus is positively correlated with its perceived duration: bigger, brighter or louder stimuli are usually perceived to last longer than smaller, dimmer or softer ones. According to A Theory of Magnitude (ATOM), temporal and nontemporal magnitudes are linked in the human mind by virtue of sharing a common metric. This claim has been challenged by studies in the domains of brightness and loudness suggesting that it is not the difference in magnitude between stimuli, but rather their degree of change from background that modulates duration judgments. But do the same relationships hold between perceived duration and all prothetic dimensions? We tested the influence of stimulus magnitude and relative change on temporal judgment in the domain of space. We found that, unlike brightness and loudness, spatial length can influence duration judgments independently of the degree of change from a common background, and that this effect is context dependent. Thus, an approach based exclusively on the degree of change between stimulus and background is not sufficient to account for the effect of magnitude on temporal judgments. Our results suggest that space has a privileged link with temporal representations compared to other prothetic domains, challenging the hypothesis that space-time relationships are the product of a domain-general magnitude system.

Keywords: ATOM; Metaphor; Space; Time; ATOC

Introduction

Judgments of duration can be influenced by non-temporal aspects of events such as stimulus magnitude (Walsh, 2003; Xuan, Zhang, He, & Chen, 2007). Bigger stimuli are judged to last longer than smaller ones (Xuan et al., 2007), brighter stimuli longer than dimmer ones (Xuan et al., 2007; Goldstone et al., 1978), and louder sounds longer than softer ones (Goldstone et al., 1978). Magnitude Effects have often been interpreted as the effect of absolute magnitude on stimulus duration: more intense stimuli seem to last longer (Xuan et al. 2007; Bueti & Walsh, 2009). It has been suggested that temporal and non-temporal magnitudes are positively correlated in the human mind by virtue of sharing a common metric (Xuan et al. 2007; Walsh, 2003). On this view, magnitudes across different prothetic domains (i.e. domains that can be experienced as 'more than' or 'less than'; Walsh, 2003) are represented in the brain by a generalized magnitude system. Duration and other prothetic domains are linked by a monotonic "more A – more B" mapping (Bueti & Walsh, 2009) such that "bigger, faster, brighter, further in one domain should correlate with bigger, faster, brighter, further in another" (Bueti & Walsh, 2009, p.1832).

In spite of a large body of supporting evidence, the hypothesis that stimulus magnitude and its perceived duration are positively correlated has been challenged. It has been suggested (Matthews, Stewart, & Wearden, 2011) that it is the relative difference between the stimuli and a common background, rather than the absolute magnitude of the stimuli, that modulates the subjective experience of duration. In one experiment (Matthews et al., 2011) participants judged the duration of two successive stimuli that varied both in duration and brightness. When the stimuli were presented on a dark background, brighter stimuli were judged to last longer than dimmer ones, on average. Yet, when the same stimuli were presented on a white (brighter) background, the opposite effect was found: dimmer (less intense) stimuli were judged to last longer than brighter ones. The same results were obtained when louder and softer sounds were presented against quiet or noisy backgrounds. Further experiments also support the hypothesis that duration judgments are proportional to the difference between the stimulus and its background. When an "oddball" stimulus is presented within a sequence of repeated presentations of a standard stimulus, the perceived duration of the oddball is exaggerated compared to the standards (Tse, Intriligator, Rivest, & Cavanagh, 2004; Ulrich, Nitschke, & Rammsayer, 2006). In the Oddball Effect the relative difference between the stimulus (the oddball) and the background (the repeated standard stimulus) has been found to predict subjective temporal dilation: The larger the difference between oddball and standard, the larger the temporal dilation (Schindel, Rowlands, & Arnold, 2011).

Moreover, the absolute magnitude of the oddball appears to be *irrelevant* for duration judgments. Schindel and colleagues (Schindel et al. 2011, Exp. 2) presented their participants with a series of gray disks (the standard stimulus) that was unpredictably interrupted by an odd disk that was either brighter (more intense) or dimmer (less intense). If the subjective duration of events is positively correlated with the absolute magnitude of these events, then dimmer oddballs should be judged to last less time compared to the brighter standard. At minimum, the absolute brightness of the oddballs should modulate their effect: Even if both brighter and dimmer oddballs were judged to last longer than the standard, the temporal dilation should be more pronounced for the brighter, more intense oddballs. Contrary to these predictions, however, stimulus magnitude had no effect whatsoever on duration judgments: Dimmer and brighter oddballs led to equivalent temporal expansion. Once again, it was the relative difference between the stimuli and the background that determined changes in subjective duration, and not the absolute magnitude of the stimuli (Shindel et al., 2011).

Altogether, these studies suggest a reinterpretation of "more A - more B" Magnitude Effects (Bueti & Walsh, 2009). We propose that these effects may be a special case of Stimulus-Background Effects. The subjective duration of a stimulus is proportional to the difference between the stimulus and its background. Magnitude Effects, then, are simply Stimulus-Background Effects for which the relative change happens to be in magnitude. The relative variation does not need to occur in prothetic domains: Similar effects have been found for variation in shape (Tse et al. 2004), complexity (Schiffman, H. R., & Bobko, 1974), color (Tse et al. 2004) and orientation (Schindel et al. 2011), which are qualitative (metathetic) domains of experience. If indeed Magnitude Effects are a species of Stimulus-Background Effects, they need not depend on any neurocognitive mechanisms that are specific for magnitude representations, but rather on mechanisms that support comparison of values along prothetic and metathetic continuums, alike (see Eagleman & Pariyadath, 2009 for a similar proposal).

To summarize, we can distinguish two theoretical approaches that seek to explain the effect of non-temporal magnitudes on temporal judgments. *A Theory of Magnitude* (ATOM; Walsh, 2003) posits that duration is positively correlated with other prothetic domains in the mind and brain by virtue of sharing the same magnitude-specific representational basis (Bueti & Walsh, 2011; Xuan et al. 2007; Walsh, 2003). Under this assumption, temporal distortions induced by variation in metathetic (qualitative) domains such as color or shape exploit different cognitive and neural mechanisms compared to similar effects induced by variation in prothetic (quantitative) domains. The alternative approach, which we will call *A Theory of Change* (ATOC), suggests instead that Magnitude Effects are particular cases of Stimulus-Background effects.

The experimental evidence reviewed above favors ATOC over ATOM. There is no special representational link between duration and prothetic dimensions, and no positive correlation between the magnitude of a stimulus and its duration: Temporal illusions attributed to the absolute magnitude of the stimuli can be explained by the relative difference between stimulus and background (Matthews et al., 2011; Shindel et al., 2011).

In this study we seek to investigate whether ATOC can fully explain the relationship between perceived duration and non-temporal magnitudes. Both ATOM and ATOC have in common the assumption that all prothetic domains influence temporal judgments in the same way. On the basis of metaphor theory (Lakoff & Johnson, 1999; Casasanto & Boroditsky, 2008), however, we predict that different nontemporal domains will influence temporal judgments differentially, depending on the relationships between these domains in our experience. Specifically, the relationship between perceived duration and non-temporal magnitude should be different for spatial magnitude than it is for other prothetic domains. That is, the relationship between space and time is special.

Space and time: an experiential link

Compared to other prothetic domains, space and time seem to be linked in the human mind by a special relationship. Across languages and cultures, spatial expressions are widely recruited to *talk* metaphorically about time (Lakoff & Johsnon 1999). These patterns in language have motivated non-linguistic experiments supporting the hypothesis that people use spatial conceptual structures to *think* about time. Across studies, stimuli that extend farther in space are judged to last longer in time (e.g., Casasanto & Boroditsky, 2008). This relationship between duration (i.e., temporal magnitude) and length (i.e., a kind of spatial magnitude) has been found in the judgments of children (Casasanto, Fotakopoulou, & Boroditsky, 2010) and infants (Srinivasan & Carey, 2010), as well as adults.

Why do many of the world's languages metaphorize duration in terms of length (e.g., a *long* time), instead of some other prothetic domain such as brightness or loudness (e.g., a *bright* time; a *loud* time)? Perhaps this is because space and time are correlated in our experience of the world in a way that brightness and time and loudness and time are not. As a moving object travels farther though space, more time passes. This positive correlation between magnitudes in space and time does not seem to exist between duration and other prothetic domains. Brighter things do not necessarily last a longer time than dimmer things (in fact the opposite may be true), and louder events do not necessarily last longer than softer ones.

Implicitly linking space and time in our minds may be useful because these domains are linked in the world. Knowing that "more space" is generally correlated with "more time" can provide a useful heuristic, facilitating interactions with our physical environment. By contrast, there does not appear to be any analogous link between duration and other prothetic domains in the world. As such, a representational link between temporal and spatial magnitudes in the human brain/mind is functionally motivated, and reflects regularities in our physical experience. But an analogous link between temporal magnitude and brightness or temporal magnitude and loudness would not have the same functional motivation, since these links would not have any clear basis in experiential regularities.

Testing for a special link between time and space

In this study, we compared the effect of spatial magnitude (specifically spatial length) and relative degree of change on duration judgments. In previous studies (Casasanto & Boroditsky, 2008; Xuan et al., 2007) the relative degree of change was positively correlated with magnitude (e.g. line length). This correlation made it impossible to tell which of the two factors were driving the effect. We designed the current experiments so that absolute magnitude of the stimuli and relative difference from the standard/background were orthogonal to each other. If the effect of spatial magnitude on time is due to the relative amount of change, we should expect that when the difference from the background is the same, stimuli with different spatial magnitudes will be perceived as having the same duration. This outcome would support ATOC, and indicate that space stands in the same relation to time as other prothetic domains (e.g., Shindel et al., 2011). Alternatively, if spatial and temporal magnitudes, per se, are linked in the mind, we should observe a magnitude effect yielding longer duration judgments for spatially longer stimuli than for spatially shorter ones. This outcome would suggest the relationship between space and time differs from the relationship between time and other prothetic domains.

Experiment 1. Long and short oddballs

In this first experiment we used a classic oddball paradigm to test the influence of stimulus magnitude on perceived duration. The standard stimulus was a 5 cm gray line, while the oddballs were lines of either shorter or longer length. If perceived duration is affected by the relative difference between the standard and the oddball (Schindel et al. 2011; Matthews et al. 2011) rather than spatial magnitude per se, both large and small oddballs should lead to the same effect of temporal expansion (i.e. a classic Oddball Effect). On the other hand, if stimulus spatial magnitude influences perceived duration (Casasanto & Boroditsky, 2008), we should expect that large oddballs should lead to a greater temporal expansion compared to smaller ones.

Methods

Participants 12 participants were recruited in the NYC area. All had normal or corrected-to-normal vision.

Stimuli. Stimuli consisted of lines of different sizes centered on a black background. The standard stimulus was a 5 cm gray (RGB 128, 128, 128) line. The oddballs were a 2.5 and 10 cm line of the same color. The width of all lines was fixed at 2 mm.

Procedure. Participants were seated in a darkened room and viewed stimuli from a distance of approximately 60 cm. For each trial 9 lines appeared sequentially in the middle of the computer screen. The standard lines (5 cm) were presented eight times in each trial with the remaining stimulus being the odd line (either 2.5 or 10 cm). Each oddball appeared unpredictably between the 5th and 8th stimuli. Oddball position was determined randomly on a trial-by-trial basis. Each stimulus was followed by a blank screen during a 300 ms ISI. Standard stimuli were presented for 500 ms, whereas oddballs were presented for 300, 400, 450, 500, 550, 600 or 700 ms. At the end of each trial, a fixation cross appeared in the middle of the screen and participants had to indicate whether the oddball had remained on the screen for more or less time than the standards. Each of the seven oddball durations was presented 10 times for each of the 2 oddballs, for a total of 140 trials. Participants completed the experiment in three blocks of 42, 42 and 56 trials. Participants responded by pressing a key with the left index finger for “less time” and a key with the right index finger for “more time” or vice versa, with key position counterbalanced between subjects.

Proportions of “more time” responses to each oddball duration were fitted using a Weibull function for individual data sets. The point of subjective equality (PSE), which is the point at which the duration of the oddball is on average judged equal to the duration of the standard, was calculated graphically as the duration corresponding to 50% of ‘‘more time’’ responses.

Results

Long oddballs led to significant temporal expansion: PSE: 480, $t(11)= 2.66$, $p= .02$; while short oddballs led to non-significant temporal contraction, PSE: 521, $t(11)= 1.39$, $p= .19$ (Fig.1, left panel).

To examine the effects of spatial length on duration judgment, we fitted a generalized linear model with binomial distribution for time judgments using the seven oddball durations and the two oddball lengths as predictors of ‘‘more time” and ‘‘less time” responses. We found that oddball spatial length influenced the oddball effect, with longer oddballs leading to a greater temporal expansion than shorter oddballs, Wald $\chi2(1)= 14.53$, $p< .001$.

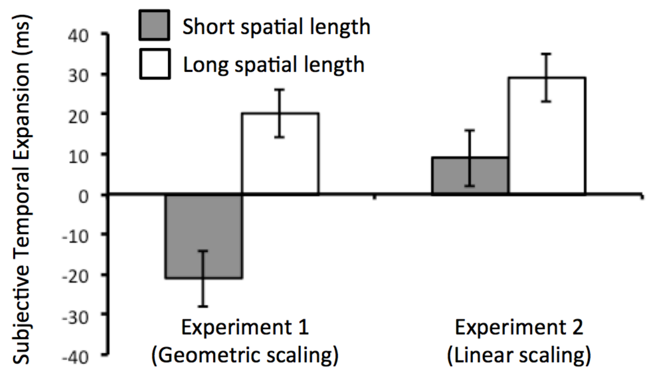

Fig1. Effect of Long and Short oddballs in Experiment 1 and 2. Error bars depict SEM (corrected for within subjects comparisons).

Discussion

In Experiment 1 the repetitive presentation of a gray line was unpredictably interrupted by the presentation of either a spatially longer or shorter line of different duration. Even though the two oddball lines had the same relative difference from the standard, spatially longer lines induced a greater oddball effect than spatially shorter ones. Moreover, while longer oddballs led to a significant temporal expansion (compared to the Point of Objective Equality (POE)), shorter oddballs led to a non-significant temporal contraction. These results suggest that the magnitude of the stimulus does influence the subjective experience of duration independently of the relative difference between stimulus and background.

Nevertheless, a different interpretation of the data is possible. Perhaps the difference between the long oddball and the standards was perceived to be greater than the difference between the short oddball and the standards. Since magnitude judgments for prothetic dimensions, including space, follow Weber's Law, we selected the three values of spatial length according to a logarithmic scale in which the central value was the geometric mean of the two extreme values. Thus, the long and short oddballs should be psychologically equidistant from the standards. Nevertheless, participants may have noticed that the difference between the long line and the standard was numerically greater than the difference between the short line and the standard. This "difference of differences" might have lead to the asymmetric results reported above.

Experiment 2. Linear scaling

Experiment 2 was designed to rule out the possibility that the difference between the longer oddball and the standard was perceived as greater than the difference between shorter oddball and standard. In this test the differences between the standard line and the longer oddball and the standard line and the shorter oddball were numerically the same.

Methods

Participants 20 participants were recruited in the NYC area. All had normal or corrected-to-normal vision.

Stimuli and Procedure Stimuli and procedure for Experiment 2 were the same as those in Experiment 1 with the following exception: Long oddballs were 7.5 cm long.

Result

Longer oddballs led to significant temporal expansion, PSE: 471, $t(19)= 2.73$, $p= .01$, while shorter oddballs led to a small, non-significant temporal expansion, PSE: 491, $t(19)= 0.82$, $p= .42$ (Fig.1, right panel).

To examine the effects of spatial length on duration judgments, we fitted a generalized linear model with binomial distribution for time judgments using the seven oddball durations and the two oddball lengths as predictors of ''more time" and ''less time" responses.

We found that oddball length influenced the oddball effect, with longer oddballs leading to greater temporal expansion than shorter oddballs, Wald $\chi2(1)= 6.00$, $p= .01$.

Discussion

In this experiment the relative difference between oddballs and standards was the same numerically for both longer and shorter oddballs. Yet, long oddballs led to a greater temporal expansion than did smaller ones. The Magnitude Effect observed in both experiments one and two seems to be proportional to the magnitude of the stimuli, independent of the degree of change (relative difference) between the oddball and the standards. These findings again suggest that the spatial magnitude of a stimulus modulates its perceived duration independently from the difference between stimulus and background. An approach based exclusively on the degree of change between stimulus and background is not sufficient to account for the temporal modulation observed.

Experiments 1 and 2 provided an interesting additional piece of evidence. Long oddballs always led to significant temporal expansion, whereas short oddballs led to non-significant contraction (Exp.1) or expansion (Exp.2). In the case of the shorter line, the effect of relative change would lead to temporal expansion (the shorter line is different from the standard), while the effect of magnitude would lead to temporal contraction (the shorter line is indeed shorter than the standard). We can hypothesize that when the two factors are in opposition they cancel each other out, leading to neither temporal expansion nor temporal contraction. That is, both the degree of change and the absolute magnitude of the stimuli contribute to the judgment of duration, and their relative weight seems to be roughly equal. However, the answer may not be so simple.

Seifried and Urlich (Seifried & Ulrich, 2010) report an experiment in which a smaller stationary disk was presented as an oddball among repetitive presentations of a bigger disk. Even though the oddball had a smaller size compared to the standard it led to a significant effect of temporal expansion (Seifried and Urlich, 2010, Exp. 3, footnote on page 97). This result is inconsistent with the hypothesis of an equal and opposite influence of magnitude and relative change, and with the effect of magnitude reported here. But in Seifried and Urlich's experiment there was only one oddball type, the smaller size-disk, instead of both a larger and smaller one. It is possible that the pattern of interaction between stimulus magnitude and degree of change is context dependent. The weight of each factor in influencing duration judgments depends on the salience of each factor in a given context. In a classic oddball paradigm, with only one kind of oddball, the direction of change (more/less) may be overshadowed by the fact that the oddball is simply different from the standard. The oddness of the oddball is a more salient feature of the event compared to its absolute magnitude. In this context the relative change is a more weighted factor than stimulus magnitude, and even small oddballs would lead to temporal expansion. Conversely, when two oddballs with different sizes are included in the design, absolute magnitude may become more salient: both oddballs are different from the standard but they differ in different ways. The oddballs aren't just odd, but either longer or shorter. The polarity of the magnitude continuum becomes more salient, leading to an increased effect of stimulus magnitude over relative change in influencing duration judgments. We designed Experiment 3 to test this hypothesis.

Experiment 3: Short oddballs only

In Experiment 3 the only oddball presented was the shorter line. If the interaction between stimulus magnitude and relative difference is context dependent, modulated by the relative salience of each factor, we should expect to see a significant oddball effect (i.e., subjective temporal expansion).

Methods

Participants. 20 participants were recruited in the NYC area. All had normal or corrected-to-normal vision.

Stimuli and procedure. In this experiment there was only one type of oddball, a gray line (same color as the standard) 2.5 cm long. Each of the seven oddball durations was presented 12 times, for a total of 84 trials. Participants completed the experiment in two blocks of 42 trials each. Otherwise, the stimuli and procedure were the same as those in experiments 1 and 2.

Results

The subjective duration of the oddballs was exaggerated compared to the standard, PSE: 480, $t(19)= 2.10$, $p= .05$. To examine the effects of context on duration judgments, we conducted a generalized linear model with binomial distribution to compare the effect of short oddballs across Experiment 1 and Experiment 3. We found that short oddballs led to a greater temporal expansion in Experiment 3 than in Experiment 1, Wald $\chi2(1)= 6.34$, $p = .01$ (Fig.2).
The same comparison between Experiment 2 and Experiment 3 didn't produce a significant result (Wald $\chi2(1)= 1.76$, $p = .28$).

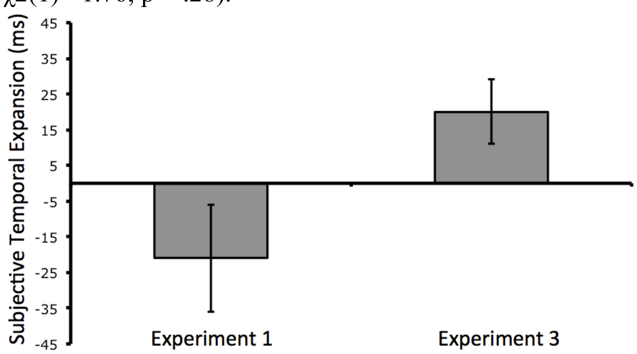

Fig2. Effect of the short oddball in Experiment 1 and 3. Error bars depict (uncorrected) SEM

Discussion

Shorter oddballs unpredictably appearing among longer standard stimuli led to a classic expansion of subjective duration, as reported by a previous study (Seifried & Urlich, 2010). These results support the hypothesis that the effect of stimulus magnitude and degree of change on duration judgment is context dependent. The more relevant one factor is made by contextual features, the more it will contribute to shaping the subjective experience of duration of a given event.

The oddball effect elicited by the short oddball in experiment 3 was significantly greater than the effect produced by the same stimulus in experiment 1, but not in experiment 2. This outcome can be explained by the fact that, in experiment 2, the difference between the standard and the shorter oddball was probably perceived as bigger compared to the difference between the standard and the longer oddball, due to linear scaling. This perceptual asymmetry may have inflated the oddball effect produced by the short-oddball. For this reason Experiment 1, in which geometric scaling was used and the relative difference between oddballs and the standard was equated, constitutes a better basis for comparison.

General Discussion

The main finding of the current research is that the absolute spatial magnitude of stimuli can influence duration judgments independently from the relative amount of change between stimuli and background. When the difference from the standard (background) was the same, oddballs that were spatially longer than the standard led to a greater subjective temporal expansion than oddballs that were spatially shorter than the standard. Space and time seem to be linked in the human mind by a positive correlation according to which objects that extend farther in space are judged to last longer (Casasanto & Boroditsky, 2008). Such a positive correlation between absolute magnitude and duration does not hold for other prothetic domains like brightness or loudness: The apparent correlation between duration and brightness and duration and loudness has been explained in terms of the relative difference from stimuli and background that modulates duration judgments, independent of stimulus magnitude (Matthews et al. 2011, Schindel et al. 2011).

Our results support the hypothesis that space and time share a special link in the human mind (Casasanto & Boroditsky, 2008; Lakoff & Johnson, 1999). This link is experientially motivated, since space and time are correlated in our everyday experience, in a way that brightness and time and loudness and time are not. The domain specificity of the link we observe between space and time is inconsistent with a domain-general magnitude metric as hypothesized by ATOM: Not all prothetic domains are represented the same way in the human mind.

Moreover, our results cannot be explained entirely as effects of the degree of change between stimuli and background. Therefore, ATOC cannot completely account for the pattern of temporal distortions observed in our experiments, either. Rather, both the spatial magnitude of the stimuli and the relative difference between stimuli and background play a role in shaping duration judgments.

The relative weight of these two factors is context dependent. When there was only one kind of oddball (Exp. 3), which was shorter than the standard, the oddball led to a classic temporal expansion. Yet, when a longer oddball was added to the design (Exp. 1 and 2), shorter oddballs were judged, on average, to have the same duration as the standard. That is, the same oddball embedded in the same sequence of standard stimuli produced different patterns of temporal distortion depending on the context in which it was presented. Such contextual variability is consistent with the hypothesis that the Oddball Effect is not mediated by low level perceptual processes like visual adaptation, but rather depends on higher-level comparison (Schindel et al. 2011) and on the contextual salience of the oddballs (Van

Wassenhove, Buonomano, Shimojo, & Shams, 2008). When *oddness* is the salient feature (Exp. 3) a “more change – more time” mapping is evident, whereas when the polarity of the magnitude continuum becomes salient (Exp. 1 & 2), a “more space – more time” mapping is also evident.

There is now considerable evidence that humans' representations of time are grounded in their nontemporal experience as well as in their temporal experience. Why should people systematically incorporate certain kinds of non-temporal information into their temporal thinking? Some non-temporal aspects of events are often good proxies for time, and they may be easier to perceive or remember than time, per se. For instance, the domain general “more change – more time” mapping, which is at the basis of ATOC, is consistent with our experience that greater changes occur over greater durations (see Fraisse, 1984). Often, amount of change may provide a perceptible basis for duration judgments: We cannot see time passing, but we can see physical objects changing (e.g., containers filling, leaves changing color, children growing). Likewise, people may rely on the domain-specific mapping between spatial extent and time because spatial aspects of our experience are generally more perceptible than the associated temporal aspects (e.g., it is possible to see how far a ball rolls (distance) but not to *see* how long it takes (duration); Casasanto & Boroditsky, 2008; Casasanto et al. 2010; Lakoff & Johnson, 1999).

Conclusions

Spatial magnitude and duration share a representational link that does not extend to other prothetic domains such as brightness and loudness. This domain specificity is inconsistent with a domain-general magnitude metric as hypothesized by ATOM. Our results are also only partly explained by ATOC as effects of a change in the magnitude of a nontemporal aspect of the stimulus. Results are best understood as supporting both ATOC and metaphor theory, in combination.

The pattern of subjective temporal expansion predicted by ATOC was observed most clearly when only one type of oddball stimulus was included, which highlighted the simple fact of a difference (i.e., change) between the oddball and the standard. The pattern predicted by metaphor theory was found most clearly when two oddballs that varied in spatial length were included, which highlighted their magnitudes.

Grounding representations of temporal magnitude in our experiences of relative amount of change (ATOC) and in spatial magnitude (metaphor theory) are both functionally motivated: As objects change, or as they travel farther through space, more time passes. As such, nontemporal aspects of events that correlate reliably with time can serve as perceptible indices of temporal change, which is imperceptible. Grounding representations of temporal magnitude in other prothetic magnitudes, however, would not be functionally motivated: The absolute magnitudes of brightness and loudness, for example, do not appear to be correlated with duration in our everyday experience. From this functional-experiential perspective, it is unsurprising that our data support ATOC and metaphor theory, but not ATOM. ATOC and metaphor theory appear to be functionally and experientially motivated in a way that ATOM is not.

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