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Perceiving numbers affects the subjective temporal midpoint

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Abstract. Temporal experience can be modulated by several environmental factors. There is increasing evidence that numerical quantity may also influence temporal processes. Here, it is shown that merely looking at numbers causes a bias in a time-bisection task that depends on its magnitude. In the first experiment, a group of healthy subjects was submitted to a time-bisection task in which numerical cues were blocked (blocked design). In the second experiment, a new group of participants performed a time-bisection task in which the previous numbers were all randomly arranged in the same block (intermingled design). Results show that temporal performance is biased when numbers of different magnitude are arranged in an intermingled design. These findings argue for a functional interaction between time and numbers, depending on the implicit extrapolation of the size difference between the displayed numbers rather than on the numerical size itself.

1 Introduction

The 'line-bisection task' is a sensitive test for attention and motor biases in both healthy and brain-damaged subjects (Fischer 2001a). In healthy subjects, performance is strongly influenced by perceptual features of stimulus-like quantities, such that when a line is composed of digits or words (2, 9 or two, nine), pointing deviates leftwards or rightwards from the midpoint (Fischer 2001b; Calabria and Rossetti 2005). It seems that numbers automatically bias attention to the left or to the right and, consequently, bisection of the lines deviates in the same direction. This effect is in accordance with a study by Fischer et al (2003), which suggested that merely looking at numbers determines a shift of attention in space. Their results showed that targets on the right were detected faster when preceded by a large digit (8 or 9), whilst targets on the left were detected faster when preceded by a smaller digit (1 or 2). A neurophysiological explanation of this effect may be derived from recent evidence supporting the hypothesis of numerical – spatial interaction within common parietal circuits concerned with attention to external space and the internal representation of numbers.

In a seminal meta-analysis, Hubbard and colleagues (2005) indicated that the bilateral horizontal segment of the intraparietal sulcus (IPS) and the lateral intraparietal (LIP) area might play a particular role in quantity and space representation. The IPS seems to be crucially activated when attention, as well as spatial updating and number processing, are involved. Dehaene and colleagues (2003) suggested that a nonverbal representation of numerical quantity, perhaps analogous to a spatial map or 'mental number line', is present in the IPS of both hemispheres. The mental number line reflects a metaphor positing that low numbers are associated with left-side space and higher numbers with right-side space (Dehaene et al 1990).

In a later study, this group (Dehaene et al 2003) also showed that the activation of IPS might extend to dorsal parietal sites that are thought to be involved in the orientation of spatial attention. Specifically, they demonstrated that verbal counting and calculation engage two additional parietal regions: a posterior dorsal parietal area that is activated by shifts in spatial attention whenever subjects count, and a left angular gyrus area that is primarily associated with the memorisation and retrieval of arithmetical facts which are thought to be stored in a verbal code (Dehaene and Cohen 1997).

In similar fashion, LIP area seems to be involved in spatial updating as well as in numerical cognition. For instance, using event-related fMRI, Medendorp and colleagues (2003) have shown that when the position of the target moved, neural activity in the LIP area also shifted, in order to represent the new spatial location of the target in eye-centred coordinates. A recent study expands this evidence showing a pattern of neural activation extending from LIP area to the posterior superior parietal lobule during the execution of addition and subtraction tasks (Knops et al 2009), as well as in the execution of tasks engaging attentional processes along the mental number line (Dehaene and Cohen 1997; Dehaene et al 2003). These facts suggest that beyond the mere encoding of quantity information per se, verbal numerical competence requires additional cognitive components.

Several of the brain areas mentioned above seem also to be activated during the performance of timing tasks. Leon and Shadlen (2003), for example, reported a link between the psychophysical performance of monkeys and single-neuron responses in the inferior parietal cortex, and argue that LIP neurons possess response properties that are related to the judgment of time. Another line of evidence arises from the discovery of 'numerons' (Nieder and Miller 2004) localised in the prefrontal cortex (PFC) and in the IPS (Wilson et al 1993), regions that are selective for both space and time processing (Harrington et al 1998; Rao et al 2001; Koch et al 2002; Oliveri et al 2009).

Furthermore, six behavioural research projects on humans have extensively shown that numerosity can affect performance in the temporal domain (Dormal et al 2006; Xuan et al 2007, 2009; Oliveri et al 2008; Vicario et al 2008; Lu et al 2009). In the study of Dormal et al, the duration and numerosity of a series of flashing dots were simultaneously manipulated in a Stroop paradigm in order to create congruent, incongruent, and neutral trials. The numerical cues conveyed by these stimuli were found to influence temporal judgment. However, temporal cues did not interfere with numerosity judgments. These results indicated that the interaction between numerosity and duration processing was limited to a unidirectional interference of numerosity with duration. A subsequent piece of research (Xuan et al 2008) reported a similar pattern of results demonstrating that even luminance changes exerted effects on the judgment of duration, suggesting an interaction of quite low-level stimulus magnitudes with temporal magnitudes. The effect of numerosity on temporal processes was also corroborated by using symbolic quantities (Oliveri et al 2008; Vicario et al 2008), while the study of Lu and colleagues (2009) made evident the importance of contextual information in inducing this effect.

Given the utility of relational inference on quantities that would extract covariance of time and numbers, one could hypothesise that common cortical mechanisms (Walsh 2003) might subserve the processing of both of these quantities. The extraction of this covariance may represent the final result of some automatic analogical processing involving frontal as well as parietal regions (Vicario and Martino 2010).

In light of this evidence, two experiments were conceived in order to expand our knowledge about the cognitive mechanisms underlying the numerical temporal interplay. In the first experiment, a group of healthy subjects was submitted to a time-bisection task in which four numerical cues (1, 2, 8, 9) were separately presented in four consecutive blocks (blocked design). In the second experiment, a new group of participants performed the same time-bisection task but with all the numbers included within the same block (intermingled design).

The purpose of the present study was to investigate whether the mere presentation of a number (blocked design) is able per se to influence temporal behaviour, or if this process requires combining digits of different size in the same block (intermingled design). None of the studies previously mentioned explicitly controlled for this factor. Through this paradigm it was also possible to explore time – numerosity interactions when using motor timing procedures. Exploring time – numerosity interactions within motor paradigms is an aspect requiring investigation, given the different neural as well as cognitive segregation for perceptual and motor processes (see Coull and Nobre 2008, for a complete review). In fact, until now there has been only one piece of recent work (Lu et al 2009) reporting time–numerosity interaction in a time production task. Therefore I submitted participants to a time-bisection task in which they were asked to represent the temporal intervals of numerical cues by means of a motor act.

In accordance with previous evidence (Xuan et al 2007; Oliveri et al 2008; Vicario et al 2008; Lu et al 2009) I expected that changing numerical size of visual cues would induce a modification of temporal bisection with an underestimation of low numerical cues and overestimation of high numerical cues.

2 Methods

2.1 *Experiment 1*

2.1.1 *Procedure and equipment.* Participants were positioned 60 cm from the monitor of a P791 Dell computer configured to a refresh rate of 100 Hz to perform a time-bisection task. After brief training, participants were asked to confront durations of 40 stimuli (2 numbers $\times$ 5 repetitions $\times$ 4 temporal intervals) centred on the screen, repeated in two randomised experimental blocks: small digits (1 and 2), large digits (8 and 9). They fixated on a black cross of 0.2 deg in diameter that was centrally located on the screen. After 500 ms, a test cue (a digit, size 0.80 deg) appeared at random subsecond durations (700, 900 ms) and suprasecond (2000, 2200 ms) intervals. Participants used their preferred hand. Their task was to time the duration of each test cue and perform a temporal bisection task. They were instructed to imagine a timer starting immediately after the disappearance of the test cue and to stop the timer when they felt that half of the test cue duration had elapsed, by pressing the space key. Participants were instructed to avoid the use of counting strategies.

2.1.2 *Participants.* Fourteen right-handed graduate students (eight men, six women; mean age: 25 ± 3.7 years) with normal or adequately corrected vision participated in the studies after providing informed, written consent.

2.2 *Experiment 2*

2.2.1 *Participants, procedure, and equipment.* Eleven subjects (four men, seven women; mean age: 24.09 ± 3.1 years) with normal or adequately corrected vision participated in the studies after providing informed, written consent. In this case all numbers (low—1 and 2; and high—8 and 9) were randomly presented in a single block. After brief training, participants were asked to compare the duration of 80 stimuli (5 repetitions $\times$ 4 numbers $\times$ 4 temporal intervals). Response parameters and other aspects of the experimental protocol were identical to those described for experiment 1.

3 Data analysis

The means of the median reaction time (RT) were analysed by using a two-way ANOVA for repeated measures, in which numerical magnitude and temporal block (subsecond versus suprasecond) were considered as interactive factors. A posteriori *t*-tests with Bonferroni correction were performed. Data analysis was performed with Statistica software, version 8.0 (StatSoft Inc., Tulsa, USA).

4 Results

4.1 *Experiment 1*

ANOVA results documented a main effect of temporal block in the subjects' timing performance ($F_{1,13} = 35.24$, $p = 0.001$). However, there was no significant effect of the within-subjects factor numerical magnitude ($F_{1,13} = 0.74$, $p = 0.404$). Likewise, there was no significant interaction of numerical magnitude $\times$ temporal block ($F_{1,13} = 0.01$, $p = 0.914$.

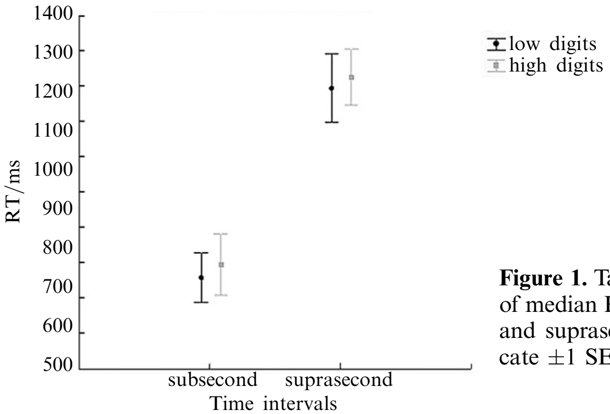

Figure 1. Task performance (experiment 1). Means of median RT values during bisection of subsecond and suprasecond intervals. The vertical bars indicate ± 1 SEM.

Subsecond block: low numbers $M = 733$ ms; high numbers $M = 765$ ms; suprasecond block: low numbers $M = 1209$ ms; high numbers $M = 1237$ ms; see figure 1).

4.2 *Experiment 2*

ANOVA results in experiment 2 showed a main effect of temporal block in the subjects' performance ($F_{1,10} = 156.16$, $p = 0.001$). There was also a significant effect of the within-subjects numerical magnitude factor on the time-bisection procedure ($F_{1,10} = 18.86$, $p = 0.001$). The global RTs in the time-bisection procedure were significantly longer when perceiving high numbers ($M = 984$ ms) compared to low numbers ($M = 920$ ms). Likewise, there was a significant interaction of numerical magnitude $\times$ temporal block ($F_{1,10} = 5.59$, $p = 0.039$, see figure 2). A posteriori analysis reported significant RT differences in the timing of low versus high numbers for suprasecond blocks ($p < 0.001$), in that the durations of low numerical cues were underestimated ($M = 1118$ ms) compared to those of high numerical cues ($M = 1210$ ms). However, no significant difference was reported for the subsecond blocks ($p < 0.388$, low numbers $M = 723$ ms; high numbers $M = 758$ ms).

Further analyses were performed in order to evaluate the accuracy in the bisection procedure. Low accuracy was evidenced in the bisection of subsecond numerical cues. A t-test against the reference (the average reference duration for the subsecond block was 400 ms) indicated a large overestimation in the bisection of both low ($t = 7.42$, $p < 0.001$) and high ($t = 9.77$, $p < 0.001$) numerical cues. However, participants were quite accurate in the bisection of suprasecond numerical cues. In this case, no significant differences were reported when comparing bisection performance against the reference (1050 ms): low numerical cues ($t = 1.21$, $p < 0.25$) and high numbers ($t = 2.56$, $p < 0.057$).

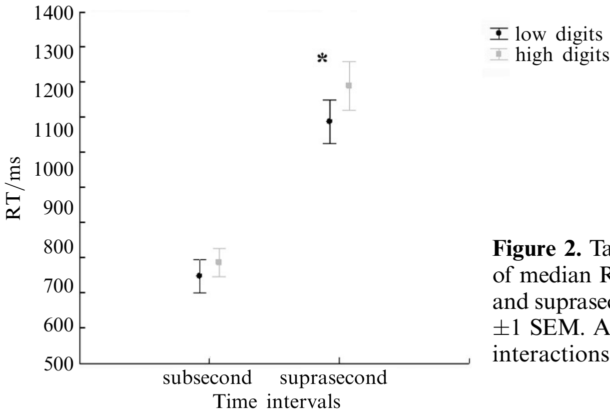

Figure 2. Task performance (experiment 2). Means of median RT values during bisection of subsecond and suprasecond intervals. The vertical bars indicate ± 1 SEM. Asterisks indicate significant a posteriori interactions.

5 Discussion

Previous studies have shown that looking at (or even thinking of) numbers influences eye movements (Fischer et al 2004; Loetscher et al 2010), spatial motor judgment in stimulus response compatibility paradigms (ie a grip closure or opening) (Andres et al 2004; Lindemann et al 2007), and action planning (Badets et al 2007). In the present work I focused on time perception and its relation to quantity. The main finding of this study was that changing the numerical size induces a modification of temporal bisection.

As previously reported (Oliveri et al 2008; Vicario et al 2008; Lu et al 2009), Arabic digits affect time bisection in such a way that durations tend to be underestimated for low numbers and overestimated for high numbers. This effect is consistently demonstrated by the significant results of both numerical magnitude and the numerical magnitude × temporal block interaction. The main effect of numerical magnitude is specified by the interaction in the way that the underestimation of temporal intervals following a small number and overestimation of temporal intervals following a large number was only present for the suprasecond conditions.

The absence of time – numerosity interplay in the blocked design (experiment 1), however, clearly indicates the importance of comparing numerical cues to each other. In fact, the influence of digits on time bisection seems to be specifically related to the intermingled design (experiment 2). Therefore, the implicit comparison of size differences across the displayed numbers, rather than the numerical size itself, seems to be the key factor underlying the present temporal bias.

One hypothesis would be that the intermingled design promotes a consistent diversion of attention along the internal left-to-right mental-number line representation. In turn, these attention shifts would be responsible for the temporal biases found in the present research, according to the 'time line' hypothesis in which temporal intervals are coded within a left to right spatial representation (Vicario et al 2007, 2009), in a similar way to numerical representations (Dehaene et al 1990). The suggestion of a critical role of spatial attention in underlying this process is supported by a body of evidence. For instance, Stelmach and Herdman (1991) provided support in favour of this assumption, showing that the perception of temporal order is influenced by allocation of attention. Moreover, a recent study demonstrated that direct manipulation of spatial attention by means of prismatic lenses (Frassinetti et al 2009) biases temporal bisection according to the side of space where attention is oriented: rightward attention shifts induce temporal overestimation and leftward attention shifts induce underestimation of temporal judgments.

That numbers modulate the timing ability of our participants by influencing the cognitive load of spatial attention is also corroborated by results of other recent research (Casarotti et al 2007), demonstrating that an important consequence of numerical processing is the automatic allocation of spatial attention, which in turn affects the perception of the temporal order of visual events. The results of the present research also show that numbers affect performance even for a motor timing procedure. Similarly to recent findings (Lu et al 2009), the tasks used here require explicit planning of actions with direct involvement of motor timing control.

It should be noted that the absence of time – numerosity interaction in the subsecond block could be explained in terms of data concerning the participants' accuracy. That is, we didn't find a time – numerosity interaction because the participants were simply not able to correctly perform the task in the subsecond condition as evidenced by the large overestimation of the numerical cues.

In summary, the bias in time bisection found in this study supports a time-line model, in parallel with the classical bisection bias using numerical strings (Fischer 2001b; Calabria and Rossetti 2005), such that the size of a number influences the subjective midpoint of a temporal duration. It has been suggested that the neural correlates of computing the midpoint of a horizontal line segment include a set of regions in the right parietal cortex (Vallar 2001; Mesulam 2002; Mort et al 2003; Oliveri and Vallar 2009). These regions seem to be also involved in the processing of time (Harrington et al 1998; Rao et al 2001; Koch et al 2002; Oliveri et al 2009) and quantity (Wilson et al 1993; Leon and Shadlen 2003; Nieder and Miller 2004). The present results are in line with the literature in showing that humans are influenced by a vectorial spatial distribution when explicitly thinking about time intervals (Oliveri et al 2009), and that the parietal cortex is a brain region that is critical for the interaction process between these two magnitudes.

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References

Andres M, Davare C A M, Pesenti M, Olivier E, Seron X, 2004 "Number magnitude and grip aperture interaction" *NeuroReport* **15** 2773 – 2777

Badets A, Andres M, Di Luca S, Pesenti M, 2007 "Number magnitude potentiates action judgements" *Experimental Brain Research* **180** 525 – 534

Calabria M, Rossetti Y, 2005 "Interference between number processing and line bisection: a methodology" *Neuropsychologia* **43** 779 – 783

Casarotti M, Michielin M, Zorzi M, Umiltà C, 2007 "Temporal order judgment reveals how number magnitude affects visuospatial attention" *Cognition* **102** 101 – 117

Coull J, Nobre A, 2008 "Dissociating explicit timing from temporal expectation with fMRI" *Current Opinion in Neurobiology* **18** 137 – 144

Dehaene S, Cohen L, 1997 "Cerebral pathways for calculation: Double dissociation between rote verbal and quantitative knowledge of arithmetic" *Cortex* **33** 219 – 250

Dehaene S, Dupoux E, Mehler J, 1990 "Is numerical comparison digital? Analogical and symbolic effects in two-digit number comparison" *Journal of Experimental Psychology: Human Perception and Performance* **16** 626 – 641

Dehaene S, Piazza M, Pinel P, Cohen L, 2003 "Three parietal circuits for number processing" *Cognitive Neuropsychology* **20** 487 – 506

Dormal V, Seron X, Pesenti M, 2006 "Numerosity-duration interference: a Stroop experiment" *Acta Psychologica* **121** 109 – 124

Fischer M H, 2001a "Cognition in the bisection task" *Trends in Cognitive Sciences* **5** 460 – 462

Fischer M H, 2001b "Number processing induces spatial performance biases" *Neurology* **57** 822 – 826

Fischer M H, Castel A D, Dodd M D, Pratt J, 2003 "Perceiving numbers causes spatial shifts of attention" *Nature Neuroscience* **6** 555 – 556

Fischer M H, Warlop N, Hill R L, Fias W, 2004 "Oculomotor bias induced by number perception" *Experimental Psychology* **51** 91 – 97

Frassinetti F, Magnani B, Oliveri M, 2009 "Prismatic lenses shift time perception" *Psychological Science* **20** 949 – 954

Gold J I, Shadlen M N, 2002 "Banburismus and the brain: decoding the relationship between sensory stimuli, decisions, and reward" *Neuron* **36** 299 – 308

Hanks T D, Ditterich J, Shadlen M N, 2006 "Microstimulation of macaque area LIP affects decision-making in a motion discrimination task" *Nature Neuroscience* **9** 682 – 689

Harrington D L, Haaland K, Knight R, 1998 "Cortical networks underlying mechanism of time perception" *Journal of Neuroscience* **18** 1085 – 1095

Hubbard E M, Piazza M, Pinel P, Dehaene S, 2005 "Interaction between number and space in parietal cortex" *Nature Neuroscience* **6** 435 – 448

Huk A C, Shadlen M N, 2005 "Neural activity in macaque parietal cortex reflects temporal integration of visual motion signals during perceptual decision making" *Journal of Neuroscience* **25** 10420 – 10436

Ivry R B, Spencer R M, 2004 "The neural representation of time" *Current Opinion in Neurobiology* **14** 225 – 232

Knops A, Thirion B, Hubbard E M, Michel V, Dehaene S, 2009 "Recruitment of an area involved in eye movements during mental arithmetic" *Science* **324** 1583 – 1585

Koch G, Oliveri M, Carlesimo G A, Caltagirone C, 2002 "Selective deficit of time perception in a patient with right prefrontal cortex lesion" *Neurology* **59** 1658 – 1659

Leon M I, Shadlen M N, 2003 "Representation of time by neurons in the posterior parietal cortex of the macaque" *Neuron* **38** 317 – 327
Lindemann O, Abolafia J M, Girardi G, Bekkering H, 2007 "Getting a grip on numbers: numerical magnitude priming in object grasping" *Journal of Experimental Psychology: Human Perception and Performance* **33** 1400 – 1409
Loetscher T, Bockisch C J, Nicholls M E, Brugger P, 2010 "Eye position predicts what number you have in mind" *Current Biology* **20** R264 – R517
Lu A, Hodges B, Zhang J, Zhang J X, 2009 "Contextual effects on number – time interaction" *Cognition* **113** 117 – 122
Medendorp W P, Goltz H C, Villis T, Crawford J D, 2003 "Gaze-centered updating of visual space in human parietal cortex" *Journal of Neuroscience* **23** 6209 – 6214
Mesulam M M, 2002 "Functional anatomy of attention and neglect: from neurons to networks", in *The Cognitive and Neural Bases of Spatial Neglect* Eds H-O Karnath, A D Milner, G Vallar (Oxford: Oxford University Press) pp 33 – 45
Mort D J, Malhotra P, Mannan S K, Rorden C, Pambakian A, Kennard C, Husain M, 2003 "The anatomy of visual neglect" *Brain* **126** 1986 – 1997
Nieder A, Miller E K, 2004 "A parieto-frontal network for visual numerical information in the monkey" *Proceedings of the National Academy of Sciences of the USA* **101** 7457 – 7462
Oliveri M, Koch G, Salerno S, Torriero S, Lo Gerfo E, Caltagirone C, 2009 "Representation of time intervals in the right posterior parietal cortex: implications for a mental time line" *NeuroImage* **46** 1173 – 1179
Oliveri M, Vicario C M, Salarno S, Koch G, Turriziani P, Mangano R, Chillemi G, Caltagirone C, 2008 "Perceiving numbers alters time perception" *Neuroscience Letters* **27** 308 – 311
Oliveri M, Vallar G, 2009 "Parietal versus temporal lobe components in spatial cognition: Setting the mid-point of a horizontal line" *Journal of Neuropsychology* **3** 201 – 211
Rao S M, Mayer A R, Harrington D L, 2001 "The evolution of brain activation during temporal processing" *Nature Neuroscience* **4** 317 – 323
Roitman J D, Shadlen M N, 2002 "Response of neurons in the lateral intraparietal area during a combined visual discrimination reaction time task" *Journal of Neuroscience* **22** 9475 – 9489
Schindler I, Kerkhoff G, 1997 "Head and trunk orientation modulate visual neglect" *NeuroReport* **8** 2681 – 2685
Sereno M I, Pitzalis S, Martinez A, 2001 "Mapping of contralateral space in retinotopic coordinates by a parietal cortical area in humans" *Science* **294** 1350 – 1354
Shadlen M N, Newsome W T J, 2001 "Neural basis of a perceptual decision in the parietal cortex (area LIP) of the rhesus monkey" *Journal of Neurophysiology* **86** 1916 – 1936
Stelmach L B, Herdman C M, 1991 "Directed attention and perception of temporal order" *Journal of Experimental Psychology: Human Perception and Performance* **17** 539 – 550
Vallar G, 2001 "Extrapersonal visual unilateral spatial neglect and its neuroanatomy" *NeuroImage* **14** 52 – 58
Vicario C M, Caltagirone C, Oliveri M, 2007 "Optokinetic stimulation affects temporal estimation in healthy humans" *Brain and Cognition* **64** 68 – 73
Vicario C M, Martino D, 2010 "The neurophysiology of magnitude: One example of extraction analogies" *Cognitive Neuroscience* **2** 144 – 145
Vicario C M, Pecoraro P, Turriziani P, Koch G, Caltagirone G, Oliveri M, 2008 "Relativistic compression and expansion of experiential time in the left and right space" *PLoS One* **3** e1716; doi:10.1371/journal.pone.0001716
Vicario C M, Rappo G, Pepi A, Oliveri M, 2009 "Timing flickers across sensory modalities" *Perception* **38** 1144 – 1151
Walsh V, 2003 "A theory of magnitude: common cortical metrics of time, space and quantity" *Trends in Cognitive Sciences* **7** 483 – 488
Wilson F A, Scalaidhe S P, Goldman-Rakic P S, 1993 "Dissociation of object and spatial processing domains in primate prefrontal cortex" *Science* **260** 1955 – 1958
Xuan B, Zhang D, He S, Chen X, 2007 "Larger stimuli are judged to last longer" *Journal of Vision* **7** 1 – 5
Xuan B, Chen X C, He S, Zhang D R, 2009 "Numerical magnitude modulates temporal comparison: an ERP study" *Brain Research* **7** 135 – 142

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