



On magnitudes in memory: An internal clock account of space–time interaction [☆]



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ABSTRACT

Traditionally, research on time perception has diverged into a *representational* approach that focuses on the interaction between time and non-temporal magnitude information like spatial distance, and a *mechanistic* approach that emphasizes the workings and timecourse of components within an internal clock. We combined these approaches in order to identify the locus of space–time interaction effects in the mechanistic framework of the internal clock model. In three experiments, we contrasted the effects of spatial distance (a long- vs. short-distance line) on time perception with those of visual flicker (a flickering vs. static stimulus) in a duration reproduction paradigm. We found that both a flickering stimulus and a long-distance line lengthened reproduced time when presented during time encoding. However, when presented during time reproduction, a flickering stimulus shortened reproduced time but a long-distance line had no effect. The results thus show that, while visual flickers affects duration accumulation itself, spatial distance instead biases the memory of the accumulated duration. These findings are consistent with a clock-magnitude account of space–time interaction whereby both temporal duration and spatial distance are represented as mental magnitudes that can interfere with each other while being kept in memory, and places the locus of interaction between temporal and non-temporal magnitude dimensions at the memory maintenance stage of the internal clock model.

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1. Introduction

Time is a paradox to the human mind. It is a ubiquitous psychological experience but imperceptible to our senses. That is, there does not seem to be a physical medium for time (like light for vision) or a bodily faculty that tunes into time (like the eye for vision). For instance, we can perceive the empty interval between two clicks and have some memory of its duration, even though none of our bodily senses appear to register the emptiness. Thus, research on time perception has focused on the cognitive processes and memory representations that underlie our capacity to perceive time, and has historically split into two largely parallel but related literatures with separate theoretical emphases and empirical effects: the representational approach and the mechanistic approach.

Since time perception does not appear to rely on any particular bodily sense, the *representational approach* to time perception concerns

the mental or conceptual representational format of temporal durations and investigates how our perception of an event's duration is influenced by other dimensions of the same event (e.g. DeLong, 1981; Piaget, 1969; Xuan, Zhang, He, & Chen, 2007). One such dimension that has been heavily investigated in time representation research is spatial distance. It has been repeatedly demonstrated that perceived duration increases as a function of concurrent spatial distance (Cai, Connell, & Holler, 2013; Casasanto & Boroditsky, 2008; Merritt, Casasanto, & Brannon, 2010). For instance, Casasanto and Boroditsky (2008) displayed a line of a particular length onscreen for a particular duration and then asked participants to reproduce the duration: they showed that participants' reproduced durations increased as a function of concurrent line length. Similarly, Cai et al. (2013) showed that participants reproduced a longer duration for a sung note if the singer in the video made a concurrent long-distance horizontal gesture compared to a short-distance one. Indeed, the ability of space to distort time relies on having a reliable, high-acuity representation of spatial distance. Cai and Connell (2015) showed that when spatial distance is perceived via low-acuity haptics (rather than high-acuity vision), it has no effect on reproduced duration; instead, the relationship flipped so that time distorted space, and reproduced distance increased with duration. These space–time interaction effects suggest a close relationship between the representations of spatial distance and temporal duration. Further work also

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suggests that time perception is influenced by other dimensions such as digit magnitude (Cai & Wang, 2014; Chang, Tzeng, Hung, & Wu, 2011; Oliveri et al., 2008; Xuan et al., 2007), numerosity (Dormal, Seron, & Pesenti, 2006; Javadi & Aichelburg, 2012; Xuan et al., 2007), and spatial size (DeLong, 1981; Rammsayer & Verner, 2014; Xuan et al., 2007).

To account for these non-temporal effects on time, some researchers have proposed that temporal durations are encoded and represented as some kind of nonverbal magnitudes, as are other quantifiable dimensions such as distance, size and numerosity (Buetti & Walsh, 2009; de Hevia, Izard, Coubart, Spelke, & Streri, 2014; Gallistel & Gelman, 2000; Walsh, 2003, 2014). These magnitudes from different dimensions share a common representational format (e.g., Lambrechts, Walsh, & van Wassenhove, 2013) and appear to be processed in the same neural circuits (e.g., Bonato, Zorzi, & Umiltà, 2012; see Buetti & Walsh, 2009, for a review). Due to the noise inherent in these representations (Gallistel & Gelman, 2000; Petzschner, Glasauer, & Stephan, 2015), it is possible for concurrently-perceived magnitudes to pull on each other such that a larger magnitude representation of a non-temporal dimension (e.g., a long line versus a short line, or a large number versus a small number) can increase the magnitude representation of a duration. In addition to accounting for the effects of nontemporal dimensions on time perception, the magnitude representation account also helps to explain recent findings that time can also exert influence on the perception of other physical dimensions such as spatial distance and numerosity (Cai & Connell, 2015; Javadi & Aichelburg, 2012; Merritt et al., 2010; Roitman, Brannon, Andrews, & Platt, 2007).

The notion of time being represented as mental magnitudes has its root in an earlier *mechanistic approach* to time perception, which stipulates that temporal durations are perceived and stored as accumulative quantities (e.g. Gibbon, Church, & Meck, 1984; Meck & Church, 1983; Treisman, 1963). The mechanistic approach has focused on how temporal durations are registered, memorized, and retrieved (see Grondin, 2010, for a review). Perhaps the most influential theory of the mechanistic approach to time perception is scalar expectancy theory (Gibbon, 1977). While the theory is incorporated in most current models of time perception (e.g. Gu, van Rijn, & Meck, 2015; Matell & Meck, 2000; Wackermann, 2011), it is probably best known as the internal clock model (Gibbon et al., 1984; Treisman, 1963; Wearden, 1991; see Allman, Teki, Griffiths, & Meck, 2014, for review). The internal clock model stipulates a timing mechanism with an internal clock system (a pacemaker and accumulator), a memory store, and a comparator.¹ The pacemaker, a continuously-running timing device, emits signals or pulses at a certain rate. When timing begins, the pacemaker is connected, via a switch, to the accumulator which collects the pulses. The accumulated pulses register the perceived duration, which may be stored and maintained in memory for later reference. When a temporal judgment is to be made, the comparator then compares the perceived duration (i.e., pulses in the accumulator) with a reference duration (i.e., pulses kept in reference memory). For example, a comparison task may require the participant to decide whether a new perceived duration is longer or shorter than a memorized reference duration, while a reproduction task may require the participant to terminate a new, ongoing duration when the accumulated pulses reach a record that is equivalent to the memorized reference duration (for formal formulations of these processes, see Gibbon, 1977; Gibbon et al., 1984).

Because perceived durations are assumed to be the accumulated quantity of pulses that are collected from the pacemaker during the accumulation stage, and stored in working memory during the

maintenance stage, the internal clock model predicts that the amount of time perceived can vary as a function of pulse accumulation and memory processes.² Indeed, external manipulations such as rapid repetitive stimulation (e.g., auditory click train, visual flicker) have been found to increase perceived duration of a stimulus (Droit-Volet & Wearden, 2002; Herbst, Javadi, van der Meer, & Busch, 2013; Ortega & Lopez, 2008; Penton-Voak, Edwards, Percival, & Wearden, 1996; Wearden, Philpott, & Win, 1999). Ortega and Lopez (2008), for instance, asked people to decide whether a target duration resembled a short or a long reference duration they had previously learnt and showed that the target duration was more often perceived to be short when the reference duration had been accompanied by a flickering dot, but perceived to be long when the target duration itself was accompanied by a flickering dot. These timecourse-dependent reverse effects support the idea that visual flicker leads to more pulses being accumulated, and hence a larger amount of perceived time for whichever duration it accompanies. Such effects may arise as result of visual flicker accelerating the pacemaker speed (Droit-Volet & Wearden, 2002; Ortega & Lopez, 2008), increasing attentional allocation to duration monitoring and allowing more pulses to be registered (Herbst et al., 2013; Zakay & Block, 1995, 1997; see also Lejeune, 1998), or triggering earlier switch-on and/or delayed switch-off of the accumulator (Penney, Gibbon, & Meck, 2000; Wearden, O'Rourke, Matchwick, Min, & Maeers, 2010). While different, these mechanisms all localize visual flicker effects in the accumulation stage of the internal clock model (we will return to this point in the general discussion).

Time perception can also be affected at the later stage of memory maintenance. Perceived durations may change as a result of reference memory interference or mixing (Grondin, 2005; Gu & Meck, 2011; Jazayeri & Shadlen, 2010; Jones & Wearden, 2004; Penney, Allan, Meck, & Gibbon, 1998; Taatgen & Van Rijn, 2011). Jazayeri and Shadlen (2010), for example, showed that when multiple durations have to be remembered, reproduced durations show regression towards the mean, with long stimulus durations under-reproduced and short ones over-reproduced. Such inter-duration interference, in the internal clock model, can be attributed to the mixing or blending between different records of accumulated pulses (i.e., different durations) within reference memory (Gu & Meck, 2011; Penney et al., 1998; Taatgen & Van Rijn, 2011). Nonetheless, while these studies did examine memory representations of duration, their focus was on interaction within the dimension of time, rather than interactions between time and non-temporal dimensions (i.e., cross-dimensional interference). One exception is Moon, Fincham, Betts, and Anderson (2015), who argued that distance and duration information may cue each other in memory and potentially lead to cross-dimensional interference. However, Moon et al.'s paradigm was unusual in that it required participants to learn and remember mappings between four different colours, response fingers, and reference distances/durations. It is therefore not clear to what extent their effects are purely distance-duration interference, or at what processing stage distance and duration interact with each other.

The above overview illustrates that, despite their shared topic, the representational and mechanistic approaches to time perception each have their own research agenda, theoretical underpinnings, and empirical effects, with little cross-reference to each other's research. The recent comprehensive review of the mechanistic approach by Grondin (2010), for instance, has no reference to theoretical accounts or empirical reports of representational interference between time and non-temporal dimensions (e.g., Casasanto & Boroditsky, 2008; Walsh, 2003; Xuan et al., 2007). The oversight of the representational approach in the mechanistic literature may be attributed to the fact that proponents of the representational approach to time perception have rarely specified a detailed process model whereby time and non-temporal

¹ While we focus on the internal clock model in the present paper, other neurobiological models have theorized that timing is driven by coincidence detection in oscillating neurons rather than by a pacemaker-accumulator mechanism (e.g. Matell & Meck, 2000, 2004; Miall, 1989). Our hypotheses and findings are consistent with both the pacemaker-accumulator and oscillating-neuron view, as they are functionally highly similar (van Rijn, Gu, & Meck, 2014). We thank Hedderik van Rijn for this suggestion.

² Duration judgements can also be affected by biases at the decision stage of certain tasks (e.g. Riemer et al., 2012; Yates et al., 2012); we return to this point in the general discussion.

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