NATIONAL AND KAPODISTRIAN UNIVERSITY OF ATHENS
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DEPARTMENT OF INFORMATICS AND TELECOMMUNICATIONS
DEPARTMENT OF PSYCHOLOGY
DEPARTMENT OF PHILOLOGY

Vasileios Kotsaris

The role of stimulus change in interval duration judgments

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Advisory committee:
Konstantinos Moutoussis, Associate Professor, National and Kapodistrian University of Athens
Argiro Vatakis, Assistant Professor, Panteion University of Social and Political Sciences
Irini Skaliora, Research Assistant Professor, Biomedical Research Foundation Academy Of Athens

Athens, Greece
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The thesis is approved

Konstantinos Moutoussis ....

Argiro Vatakis ....

Irini Skaliora ....

Abstract

To inform our sense of the elapsed time, we intergrade temporal cues based on changes of our internal and external world over time. Therefore, dynamic stimuli have long been studied on their effects on duration estimates. However, it is not yet clear which aspect of change is the critical factor that affects perceived time. In our study, we tested three theories that account for how the transformations of a stimulus in a time interval relate to its perceived duration, where the first one emphasizes the role of the absolute number of presented changes, the second one the saliency of the changes, and the third one the neural energy expended to processing its content. We examined, additionally, the significance change's awareness and the modulatory role of attention on perceived duration of suprasecond intervals. Our experimental method included a dual task in a flickering paradigm with a change detection task and a temporal reproduction task. We used simple visual geometrical stimuli one of which had a positional change, throughout a trial's duration, which was masked due to the flickering presentation. The timing of perceived change was recorded to examine how attentional distribution affects duration estimates and change's awareness was assessed in a 4 alternative forced choice task. To independently modulate the neural energy for stimulus processing and the change's saliency, we manipulated: the number of presented objects (Experiment 1), their presented duration, without changing the interval's duration (Experiment 2), and the color of the stimuli with a positional change (Experiment 3). Our results did not consistently follow the predictions of any change-related account, although judged duration was affected from the number of perceived changes in about half of our experimental conditions (in Exps. 1 and 2). Change's detection influenced perceived time only when reached awareness. Attention elicited a minor direct impact on duration judgments and had a weak effect in cases where increased allocation to temporal processing lengthened subjective time according to the Attentional Gate Model. Overall, our findings indicate that in the presence of a salient and predictable flickering stimulus that provides a coherent temporal structure and entrains attention to oscillate, events presented out of this temporality and other, non-temporal, parameters, cannot override the influence of flicker's frequency on duration estimates.

Keywords: perceived duration; change perception; phenomenal awareness; attention.

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The role of stimulus change in interval duration judgments

Introduction

Our everyday temporal computations are fairly accurate. We reach our hand to hand to catch a thrown ball the right movement and we rush, usually, and manage to an arrive to the train station before a particular time. This nearly perfect performance produces the illusion that subjective time is identical to physical time. However, other incidents of our experience as well as plenty of experimental evidence indicates that experienced time systematically differs from physical time, since subjective time is influenced by many sensory and cognitive factors (e.g., Grondin, 2010; Matthews & Meck, 2014; 2016). Contextual information, emotional state, attention and other cognitive factors (Matthews & Meck, 2016; Spencer, Karmakar, & Ivry, 2009; Tse, Intriligator, Rivest, & Cavanagh, 2004) as well as intrinsic to stimuli factors such as motion, numerosity, intensity, and sensory modality are considered to affect subjective timing. (Brown, 1995; Eagleman & Pariyadath, 2009; Grondin, 2010; Matthews & Meck, 2016; Xuan, Zhang, He, & Chen, 2007). Especially, the transformations of dynamic stimuli over time have been regarded as significant indicators of the passage of time.

Attempting to address the relationship between the perception of dynamic stimuli and subjective time, numerous studies and theoretical investigations have focused on how perceived changes affect perceived duration (e.g., Brown, 1995; Kanai, Paffen, Hogendoorn, & Verstraten, 2006; Poynter, 1983; 1989). In most studies of timing, change is characterized by either shifts of spatial location of a moving stimulus or non-spatial alternations of a flickering stimulus (Linares & Gorea, 2015; Kanai et al., 2006). In general, experiments using dynamic visual stimuli have demonstrated that a moving stimulus is judged as lasting longer than a stationary stimulus of the same physical duration (Brown, 1995; Goldstone & Lhamon, 1974). Moreover, the magnitude of speed is an important factor since the perceived duration of a fast moving stimulus is lengthened as compared to the perceived duration of a slow moving stimulus (Brown, 1995). Additionally, stimuli flickering in high frequency have longer perceived duration than those of lower flickering frequency (Kanai et al., 2006; Plomp & Gepshtein, 2012). However, several findings question the existence of a monotonic or linear relationship between

speed/flicker rate and duration expansion (Herbst, Javadi, van der Meer, & Busch, 2013; Kanai et al., 2006; Linares & Gorea, 2015; Sgouramani & Vatakis, 2013; Treisman & Brogan, 1992). Interestingly, Sgouramani and Vatakis (2013) presented participants with naturalistic stimuli and found that perceived duration decreased with increasing speed and, similarly, Herbst et al. (2013) reported a decrease of time dilation with increased flickering rate. In contrast, Treisman and Borgan (1992) found that perceived duration increases as a function of temporal frequency of a flickering visual stimulus, yet in a non-linear fashion. In addition, Kanai et al. (2006) observed that the monotonic increase of time expansion with temporal frequency was followed by a plateau at 8-10 Hz. These findings suggest that a higher speed or temporal frequency does not always result in a higher expansion of subjective time, while the factors affecting the relationship of the number of changes and perceived duration are not yet determined. In sum, the evidence support a strong dependence between stimulus change and subjective timing, however, the exact characteristics of this relationship are not yet clear.

It is well-established that all of the previous types of dynamic stimuli influence timing, however, there is a disagreement on whether speed or temporal frequency are the critical parameters that induce the phenomenon of subjective time dilation (Kanai et al., 2006; Kaneko & Murakami, 2009). In order to address the underlying mechanism(s) of the phenomenon of time dilation, several studies have manipulated speed, temporal frequency, and other stimulus parameters independently (Kanai et al., 2006; Kaneko & Murakami, 2009; Linares & Gorea, 2015). However, the results reported were mixed. This controversy has important implications regarding whether early visual areas (such as V1) or hierarchically higher areas (like MT) of visual perception are linked to temporal computations. Linares and Gorea (2015) in an attempt to elucidate the previous conflicting findings (Kanai et al., 2006; Kaneko & Murakami, 2009), manipulated independently speed, "local" low-level sensory temporal frequency (defined as point changes of luminance on stimulus motion trajectory), and "global" perceptual temporal frequency (defined as stimulus rotational frequency). They asked participants to estimate the duration of moving stimuli with the method of single stimuli in intervals ranging from 0.7 to 2.5 s. The stimuli used were either one or two blobs rotating on a circular trajectory with varying speed and radius. They found rotational frequency to be the most important factor in

determining perceived duration, while the radius of the trajectory had no effect. A significant effect of speed was also reported but only for short durations and slow rotational frequencies, since in this case angular motion provided less temporal information than speed. In sum, the findings of this study indicate that the most salient events at the level of the whole perceptual experience primarily determine subjective duration rather than low-level sensory changes.

Recent findings on the effect of apparent speed on subjective duration further support that temporal cues of changing stimuli stem from higher-order visual processing (Gorea & Kim, 2015; Orgs, Bestmann, Schuur, & Haggard, 2011; Yamamoto & Miura, 2012). For example, Gorea and Kim (2015) attempted to differentiate the perceived speed of moving Gabor patches from their actual speed by presented them against a moving background. More specifically, the Gabor patches were at the center of an area filled with black dots moving in the same direction as the Gabor carriers, in the opposite or an orthogonal direction. As a consequence, the perceived speed of Gabor patches was modulated by background motion. The perceived speed and duration of the Gabor patches, presented for 500, 900, or 1300 ms, was assessed using a staircase procedure and the method of constant stimuli. The results showed that apparent speed had greater modulatory effects than physical speed since the first dilated perceived duration at a level of 20%, while the latter had a distortional effect of only 7%. Likewise, Yamamoto and Miura (2012), showed, using moving plaid patterns consisting of moving overlapping gratings of variable orientations and speed, that perceived duration increased with pattern speed but not with component speed. Similar findings have been reported from studies with biological motion (Orgs et al., 2011; Orgs, Kirsch, & Haggard, 2013). However, it has been demonstrated that - keeping the number of changes fixed – perceived duration decreases with increasing implied velocity of movement (Orgs et al., 2011).

Visually-induced time distortions caused either by speed or temporal frequency have been observed in both subsecond (Kanai et al., 2006; Kaneko & Murakami, 2009; Plomp et al., 2012; Treisman & Brogan, 1992) and suprasecond time intervals (Brown, 1995; Matthews, 2011). This is of particular importance since it has been postulated that different timing mechanisms, with distinct neural machinery, support temporal computations in the timescale of milliseconds and in the timescale of seconds or minutes (Lewis & Miall, 2003). According to this

theory, the subsecond timing is performed in an automatic and unconscious fashion, and it is mostly related to motor control. In contrast, the suprasecond timing mechanism is considered as cognitively mediated involving attentional and memory functions, to support explicit temporal judgments and general decision-making processes. Therefore, the rate of change in an interval could differentially affect time perception according to its duration (Bar-Haim, Kerem, Lamy, & Zakay, 2010; Nather, Bueno, Bigand, & Droit-Violet, 2011).

Apart from stimulus transformations, perceived duration appears to interact with other stimulus parameters that could be either perceptual, such as luminance and size, or abstract, such as the numerical value (Xuan, Zhang, He, & Chen, 2007; Oliveri et al., 2008; Walker & Scott, 1981). In this line of work, Xuan et al. (2007) studied non-temporal magnitude effects by manipulating the number of dots, the size and luminance of squares, and the numerical value of stationary visual stimuli. Using an interval comparison procedure, a general magnitude effect of these non-temporal dimensions on duration judgments was demonstrated. However, studies that manipulated both speed and numerosity in the same experiment provided conflicting results regarding the efficiency of magnitude effects on the perceived duration of dynamic stimuli (Brown, 1995; Linares & Gorea, 2015).

The above-mentioned findings have been addressed by many psychological and neural timing accounts (Gorea, 2011; Matthews & Meck, 2016). Many theorists noticed that the number of changes in a stimulus is related to its perceived duration (Fraisse, 1963; Poynter, 1989). Fraisse (1984) posited that the number of perceived changes determines subjective duration. In the same line, Poynter (1989) proposed a change-segmentation (CS) model for interval timing suggesting that changes index the passage of time by the segmentation of perceptual experience. It was also added that duration judgments are not merely determined by the absolute number of changes but also by the storage and organization of these events in memory (Poynter, 1983; Poynter & Homa, 1983). Therefore, CS approach accounts for the degree of contextual change, the discreteness of change, as well as the distribution of changes in an interval. Apparently, these theoretical accounts that emphasize the role of the number of changes in duration judgments could explain why faster moving or flickering stimuli have greater apparent duration than slower stimuli. However, such a change-based account appears

inadequate to address the non-linear, non-monotonical, or even inverse relationship between speed (or temporal frequency) and perceived duration observed in several studies (Herbst et al., 2013; Orgs et al., 2011; Sgouramani & Vatakis, 2013; Treisman & Borgan, 1992). Moreover, change-based accounts cannot explain the magnitude effects on time perception (Xuan et al., 2007), unless low-level sensory changes are considered.

Another theoretical perspective, which could account for the effects of perceived changes on perceived duration, has been proposed by Eagleman and Pariyadath (2009). In this approach, the explanatory timing variable shifts to the neural level and perceived duration is considered to be a function of the neural response energy within the to-be-timed interval. This approach had been firstly formulated to address the effects of stimulus repetition on perceived duration, supporting that "repetition suppression" results from the "sharpening" - that is, more efficient coding - of objects representation (Eagleman & Pariyadath, 2009; Grill-Spector, Henson, & Martin, 2006). In this way, it was explained why unexpected or novel objects appear to last longer and evoke stronger neural response than expected or previously presented ones (Pariyadath & Eagleman, 2007; Tse et al., 2004). Neuroimaging recordings furthermore suggest that the neural energy account could address how dynamic stimuli modulate subjective duration. At first, it has been observed that moving stimuli activate more brain areas compared to stationary ones (Dupont, Orban, Bruyn, Verbruggen, & Mortelmans, 1994). In addition, the amplitude of neural response evoked by a moving object as recorded with EEG (Mayo & Sommer, 2013) and fMRI increases as a function of its speed (up to some speed value; Chawla, Phillps, Buechel, Edwards, & Friston, 1998), and the fMRI signal of V1 activation, reflecting the processing of a flickering stimulus, increases with flicker rate up to 8 Hz (Kaufmann et al., 2001). Moreover, the neural energy account could explain the effect of stimulus complexity on perceived duration (Ornstein, 1969; Poynter, 1989; Shiffman & Bobko, 1974), since more complex stimuli patterns require greater processing resources and storage size and, thus, induce more extended neural activation than less complex stimuli.

Attention is a significant stimulus-external parameter in timing, although it has been reported to modulate perceived duration in both a bottom-up and a top-down fashion (Grondin, 2010; Matthews & Meck, 2016). An unquestionable conclusion in attention-related

timing literature is that when more attention is allocated to the passage of time, perceived duration is expanded and temporal judgments are more precise (Block, Hancock, & Zakay, 2010). Most perspectives on timing have explained these effects by assuming that computation of temporal and non-temporal information is performed on shared and limited processing resources (Buhusi & Meck, 2009; Zakay & Block, 1997). Consequently, the processing of non-temporal dimensions is executed at the expense of temporal measurements. The Attentional Gate Model (Zakay & Block, 1997) based on the previous acknowledgments and using the Internal Clock Model formulation (Church, 1984), has been proposed to describe that the allocation of attention affects duration judgments in dual-task paradigms. Under various experimental conditions, it has been shown that the compression of perceived duration and the variability of temporal estimations are proportional to the cognitive load devoted to the non-temporal task (Block et al., 2010; Brown, 1997). Similar results have been obtained, in the absence of a secondary task, but when a secondary signal or a break interferes with the processing of the target stimulus (Casini & Macar, 1997; Fortin & Masse, 2000). These findings have been explained presuming a partial allocation of attention away from the temporal task, while participants expected the interfering event, resulting in restricted accumulation of temporal information.

However, it has also been suggested that even in single-tasks without any intervening events when the stimulus to-be-timed is more demanding in terms of perceptual processing then less resources are directed to the elapsed time (Angrilli, Cherubini, Paverse, & Manfrendini, 1997; Sgouramani & Vatakis, 2013). Conversely, a vast literature regarding the effects of selective attention on duration judgments, supports that when a stimulus is preferentially processed relative to its context, it has proportionally increased perceived duration (Matthews & Meck, 2016; Tse et al., 2004). For instance, either by exogenous (Yeshurun & Marom, 2008) or endogenous cueing (Mattes & Ulrich, 1998), directing attention to the spatial location where the target stimulus is presented increases its perceived duration. Importantly, a trade-off between processing the perceptual content and the temporal properties of the stimuli has been postulated (Plomp et al., 2012). Plomp et al. using flickering light at 3 or 7 Hz, showed that higher flickering rate increases time dilation, but also reduces

sensitivity to stimulus duration, a pattern of results opposite to those observed in temporal estimations in most dual-task paradigms (Block et al., 2010).

The study by Coull et al. (2004) further illustrates how the allocation of attention between temporal and non-temporal processing affects duration estimations, while linking these operations with their neurobiological underpinnings. Using event related functional magnetic resonance imaging (fMRI), they monitored brain functioning of participants that had to attend either to the color or to the temporal properties of a stimulus. Manipulations of attention indicated a greater activation of the relating to the task brain region, while the extent of neural activation was positively correlated to the task's performance. Thus, more accurate duration judgments were performed at the expense of non-temporal perceptual processing. Although this findings suggests a localized and dedicated neural timing mechanism, it is not clear whether perceived duration is related to the activation amplitude of specialized time processing neural populations, to non-temporal visual processing brain regions, as the neural energy account implies (Eagleman & Pariyadah, 2009), or to both processing levels. Nevertheless, the observed positive correlation between attention and neural response (Coull et al., 2004) indicates that, in single-task conditions, the neural energy account could follow the predictions of the attention-based accounts that postulate perceived duration of an object to be a function of the attention that it draws (Tse et al., 2004).

Herbst, van der Meer, and Busch (2012) studied the role of attention in a different framework by examining how the interaction between attentional selection and change perception affects subjective duration. In their study, the to-be-timed interval stimuli were presented in a rapid serial visual presentation (RSVP) mode using two similar paradigms. The series of stimuli consisted of target stimuli and distractors. In the repetition blindness paradigm, the two successively presented targets were identical, while in the second one they differed. This rapid sequential presentation could mask the second target, since attention was still devoted to the perceptual processing of the first. In this case, the second target could not be consciously detected, but only processed at a low sensory level. Therefore, attentional selection determined whether or not a target-stimulus would be identified and registered in memory. And by asking participants to report the number of the detected targets after estimating the

interval's duration, it was examined whether automatic stimulus processing affected subjective duration. The results indicated that when more targets in an interval were attended, and, thus, fully processed and recalled afterwards, the perceived duration of those intervals was more lengthened as compared to trials with fewer recalled targets. The authors interpreted these findings suggesting automatically processed stimuli not to affect duration judgments more than distractors. However, no comparing condition with less distractors was used to validate this conclusion. But most importantly, in some trials the reported targets (three) were more than the actually presented ones (two), indicating the influence of a response bias, apart from the perceptual effect of target detection. Additionally, these experimental manipulations could not adequately address how the allocation of attention influences subjective duration since it is confounded with the number of targets, either reported or perceived.

In a subsequent study, Herbst et al. (2013) examined in broader perspective, which aspect of change perception mostly determines subjective duration. The changing stimulus used was a light flickering at various frequencies (3.7-165.7 Hz) presented for durations in the peri-second range. The predictions of three accounts, addressing the effect of the flickering stimulus on perceived duration, were tested. The first, named rate-of-change account, postulates that either perceived or (undetected consciously) sensory changes predict duration judgments, and thus, perceived duration would increase linearly with the rate of stimulus change up to the perceptual flicker fusion threshold (FFT) or the neural threshold (reached at frequencies greater than of the FFT) respectively. The second, named change-saliency-account, posits that the most salient frequencies (8 - 15 Hz) would induce greater temporal distortions than the less salient ones. In the third theoretical approach, the predictions as derived from the neural-energy account suggested perceived duration as a function of the steady state visual evoked potential (SSVEP) recorded in the EEG. Since perceived salience of flickering frequencies parallels the strength of the underlying neural response, with both peaking at 15 Hz (Pastor, Arlieda, Arbizu, Valencia, & Masdue, 2003; Shady, MacLeod, & Fisher, 2004), the latter two accounts provided similar predictions, only differing on whether duration judgments are influenced by frequencies higher than those of the FFT that still evoke some neural response. For the estimation of perceived duration, a double staircase method was used with a test stimulus of varying duration

(0.5 – 3.5 s) and a comparison stimulus of 2s duration. Participants were presented with the flickering light wearing a pair of goggles. On the contrary to previous findings (Kanai et al., 2006; Treisman & Borgan, 1992) and to the predictions of both the rate-of-change and change-saliency account, the results revealed an inverse relationship between time dilation and flicker rate. However, in support of the change-saliency account, within temporal frequencies, time dilation was positively related to the perception of the stimulus as flickering. Notably, time dilation occurred only at frequencies perceived as flickering (i.e., up to the FFT for each participant). Lastly, SSVEP amplitudes were not correlated with duration overestimation within each temporal frequency, however, they decline with increasing flicker frequency. Thus, the SSVEP amplitude across frequencies was related to duration judgments as the neural energy account predicts. In sum, these findings clearly oppose the rate-of-change account, while they could be not considered unequivocally in favor of either the change-saliency or the neural-energy account.

Herbst's et al. (2013) study, could not fully addressed the predictions of the three examined theoretical approaches, mainly due to the stimuli and the imaging technique used. In contrast to previously used configurations (Kanai et al., 2006; Shady, MacLeod, & Fisher, 2004; Treisman & Borgan, 1992), in this study the flickering was covering the whole visual field, and that possibly produced earlier and stronger adaptation due to the more intense, and less complex, visual stimulation. Moreover, a flickering stimulus does not provide a rich visual experience that could induce a broad characterization of change saliency, since the perceptual characteristics of a flickering light are tightly depended on low-level sensory processing. Regarding the estimation of FFT, the high variability of responses suggests a high subjectivity of the measurement, which derives from the difficulty, at high frequencies, to discern between a steady light with optical noise and steady-like fast flickering light. Furthermore, the responses of striatal cortex recorded on SSVEP result from the entrainment of a specific neural population and, thus, do not necessarily reflect the whole extent of perceptual and temporal processing in this area. Additionally, since both the steadily declining neural response with flickering rate and the change detection are postulated to shorten subjective time, their distinct effects could not be differentiated. Therefore, due to this unseparated contribution, and the imprecise

determination of the FFT, Herbst et al.'s (2013) methodology could not determinately account for the potential effect of unconscious change detection. Finally, a critical issue not examined in Herbst et al.'s (2012; 2013) studies, is whether unconscious change perception, that is cognitively accessible yet to influence subsequent behavior, has an impact on duration judgments.

Whereas stimulus transformations have been studied extensively in timing research, it is unclear exactly how and when perceived changes affect duration judgments. Previous research has provided mixed evidence about the relationship between the number of changes and perceived duration (Herbst et al., 2013; Kanai et al, 2006; Linares & Gorea, 2015). Moreover, the potential role of phenomenal aspects of visual change and its neural correlates on perceived duration have only been examined using visual stimuli of simple perceptual attributes (Herbst et al., 2013). And most importantly, it has not yet been clearly addressed how the awareness of change affects timing compared to unconscious change perception (Herbst et al., 2012; 2013). Finally, concerning the role of attention, it has not yet been clarified whether higher visual processing demands result to decreased duration estimates (Sgouramani & Vatakis, 2013) or greater selective attention to a stimulus, increases its judged duration, irrespectively of the distribution of attentional resources between temporal and non-temporal processing (Brown, 1995; Mattes & Ulrich, 1998; Tse et al., 2004).

Hence, the present study aims to examine whether the effect of change perception on subjective duration depends on the number of changes, the phenomenal experience, or the neural processing of the changing stimuli. The qualitative and quantitative significance of change perception was assessed via the formulation of three relative accounts, similar to the ones Herbst et al. (2013) suggested. Particularly, the rate-of-change account is converted to the number-of-change account, where only the absolute number of physical or perceived changes relates to the judged duration. The second one is the change-saliency account that suggests that the extent of change prominence is positively related to subjective duration. Last, the neural-energy account predicts stimulus judged duration to be a function of the extent of neural resources expended to its processing. Neural energy was assessed indirectly based on known processing resources required for computing specific stimulus characteristics, and, thus, it is

directly related to the corresponding attentional load. Additionally, we specifically examined how the allocation of attention to change detection and temporal processing modulates perceived duration. Of note, studying perceived duration of intervals in the supra-second range, a time-scale where timing is considered as cognitively mediated, the awareness of change could be of pivotal importance (Lewis & Miall, 2003). Thus, our experimental manipulations besides dissociating physical and perceived change, aimed to differentiate between unconscious and conscious change detection. By considering change awareness, we attempted to clarify whether duration estimates derive from an unconscious metric representation for motor control or they are subject to aspects of phenomenal consciousness (Montemayor, 2017).

We tested the above-mentioned predictions with an experimental set up that facilitates the differentiation among the various types of change processing. For the dissociation between physical (or low-level sensory changes) and perceived changes, we utilized the masking technique of Rensink's (1997) flickering paradigm that conceals an otherwise visible change in the visual field. This phenomenon, named "change-blindness", has been manifested under various experimental conditions, with images of varying complexity and even where abstract objects were presented (Hewlett & Oezbeck, 2013; Rensink, 1997; 2000; Scholl, 2000). In the present study, therefore, we opted to present images of simple geometrical shape, which allowed for various controlled experimental manipulations, while still rendering a change in the visual field invisible for a prolonged period of time. In the paradigm adopted, two images were sequentially presented and interrupted by an interstimulus interval (ISI) of a uniform blank field. The images were identical except from a specific change that was to be detected. The images and the ISI were of varying duration and this manipulation could either facilitate or hinder change detection and also modulate the temporal frequency of the resulting flickering presentation. Despite being repetitively presented, the change could stay undetected after several seconds/presentations since the ISI prevented the formation of a stable and memorable visual representation (Rensink, 2000). Only when selective attention is directed to the location of change, the integration of visual information results to the formation of lasting – and, thus, comparable - large-scale objects. Therefore, in our study, by using different display modes, we modulated the processing of the visual field to study the relationship between change

perception and subjective duration in broad perspective, since perceptual change was referred to both the flickering alternations of the whole visual display and to the detection of localized salient changes. And most importantly, applying the above masking technique, we could dissociate low-level sensory changes from higher-order categorical perceptual change.

Moreover, to examine whether awareness of change detection affects duration estimates, we assessed change detection using a forced choice response task. Previous studies have indicated that a change in the visual field could be detected even without participants' awareness (Fernandez-Duque & Thornton, 2000) or an accompanied visual experience (Rensink, 2004). Based on these findings, we used a 4 alternative forced choice (4AFC) task, where participants were instructed to report the quadrant where the change appeared or to guess when they lacked awareness of any change. Thus, using this response method we could assess whether behavioral performance or phenomenal experience of change perception are related to perceived duration of intervals in the supra-second range. Additionally, we recorded change detection and its precise timing to examine how the occupation of attention for visual search affects perceived duration.

In order to ascertain the effect of stimulus change on perceived duration, we designed a dual task, which includes the flickering paradigm for the change detection task and a prospective temporal reproduction task. Then, we assessed which theoretical framework is apt to explain how the response type, the quantity, and quality of change, and attention processes influence the registering and reproduction of a time interval.

Methods

Experiment 1

In the first experiment, we manipulated stimulus complexity in order to modify the number of low-level sensory changes, change salience, and neural processing demands. The display images consisted of abstract identical geometrical objects, randomly distributed (see Figure 1). Change was defined as the slight positional shift of one object between two alternating images, while image complexity was defined by the number of elements presented (i.e., increasing the number of objects lead to increased image complexity; Hewlett & Oezbeck,

2013). More objects induce light fluctuations of greater extent and, thus, more changes - retinotopically coded - in early visual areas. Moreover, previous studies have also provided mixed results about the effect of numerosity of moving stimuli (Brown, 1995; Linares & Gorea, 2015). Thus, by modulating the number of presented objects, we could clarify whether stimulus numerosity or/and alternations of low-level neural populations affect duration judgments, when temporal information is primarily provided by the flickering rate and influenced by the detection of salient perceptual changes. Furthermore, an image with higher number of objects induces more distributed visual spatial attention, and consequently less selective attention in each object. With reduced selective attention the degree of visual processing between the objects and the background is less differentiated, and as a consequence, change does not pop out as vivid as if fewer objects were presented. On the other hand, since more complex stimuli require more cognitive and neural processing resources, the increased complexity induces stronger neural response throughout the interval. Additionally, we exploited the variable timing of change detection to examine whether perceived duration is a function of either the extent of temporal processing or the overall devoted attention to the visual display processing. Before change detection, apart from the accumulation of temporal information, significant part of attention is drawn to visual processing. In contrast, after change detection, more attention is devoted to the lapse of time, however, the overall cognitive resources occupied for the processing of the visual display would decrease.

Modulation of visual complexity will allow testing the following predictions regarding how change perception could affect subjective duration. If perceived duration depends on the aggregate of perceived changes then, according to the number-of-change account, change detection would result in longer temporal reproductions irrespectively of the image's complexity. However, if early processed sensory changes or numerosity also affect perceived duration, subjective time would be more expanded with higher complexity. Moreover, the change-saliency account predicts that complexity is inversely proportional to perceived duration since higher complexity renders the change perception less vivid. In contrast, the neural-energy-account posits that higher complexity contributes to the lengthening of perceived duration. In addition, if change's awareness is a modulatory factor, then conscious change detection should

differentially affect perceived duration. Due to the fact that estimating supra-second temporal intervals strongly depends on phenomenal visual experience, we expect the change's saliency and awareness to be the major modulatory factors of duration judgments. On the other hand, in the absence of change detection, the attention-based model supports that perceived duration should be positively related to the image's complexity, while a negative relationship between perceived duration and complexity could only be assumed by the AGM theory. Furthermore, we expect that devoting attention in searching for a change to impair the accumulation of temporal information, and, thus, when change detection comes earlier would result in longer temporal reproductions. However, as the neural-energy account (or the Attention-based timing account) would predict, if the overall cognitive effort in processing the flickering presentation dilates subjective time, then earlier change detection would shorten perceived duration.

Participants

Thirty-eight participants took part in the experiment (25 females) aged between 18 and 45 years old (mean age = 28 years of age). Participants reported normal or corrected-to-normal vision, while participants with epileptic disorders where excluded.

Apparatus

The experiment was conducted in a dark and quiet room. Stimuli were designed and presented using OpenSesame v3.1 (Mathôt, Schreij, & Theeuwes, 2012). We used a CRT monitor with 60 Hz refresh rate and 1600x1200 resolution for stimulus presentation. The participants sat at a 60 cm distance from the computer monitor.

Stimuli and design

Participants were presented with a flickering visual display consisting of two main images (I and I') and an ISI between them. The two images were presented interchangeably for 200 ms each, while the ISI was 80 ms. Thus, during the to-be-timed interval, the blank ISI and the images alternated to produce a flickering display. Given the duration of the images and the ISI, the flickering presentation had a temporal frequency of 7.2 Hz. During the ISI, a uniform blank field of black color was presented, which served as a mask. The two stimulus images had a

uniform dark grey background with identical white squares (20x20 pixels) being randomly distributed throughout the display. The images differed only in respect to the position of one, randomly determined, square with a horizontal displacement of 27 pixels. For the lowest complexity level, 20 squares appeared, while for the highest level of complexity, 30 squares were presented. Prior to the to-be-timed interval, a white fixation cross was presented at the center of the display. The interval to be timed started and ended with the appearance of an image. The duration of the interval to be timed was 1.6, 2.72, or 3.84s (corresponding to 3, 5, or 7 image alternations).

The experiment was composed of 6 experimental conditions resulting from the two types of stimulus complexity and the three interval durations. The change detection task included 10 trials for each condition, preceded by 9 practice trials. Participants were presented with two blocks of 42 trials. 12 trials in each block were without rectangle's dislocation (catch trials), with 4 trials for each interval's duration. In the first block the low stimulus complexity level was presented and the high stimulus complexity level in the second, always in this order. In each block, all durations and catch trials were randomly presented. Between the two blocks, participants had the opportunity to have a break for as long as they wanted.
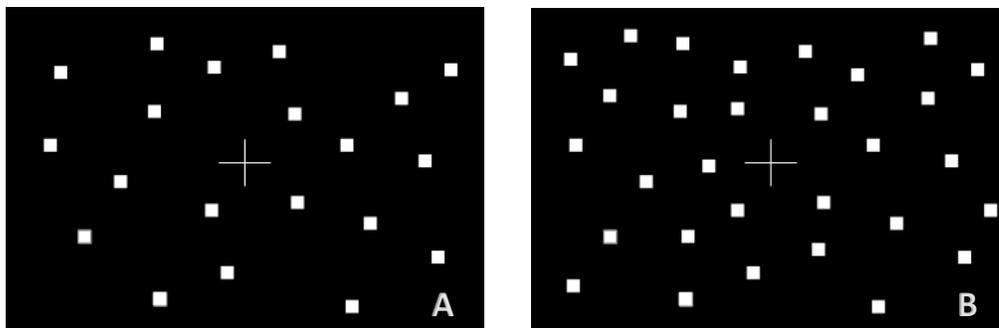
Figure 1. Images of the presented stimuli in the two complexity levels with 20 (A) and 30 (B) rectangles. The position of one of these rectangles changes in the subsequent image after the ISI.

Procedure

At the beginning of each trial, participants had to fixate on the white cross at the center

of the display. They were then instructed to search for a change in the images presented. When the rectangle's displacement was clearly detected, participants had to immediately respond by pressing a specific button. After the change's detection, a free observation at the display was suggested, until interval's termination. Afterwards, participants had to reproduce the duration of the previously presented interval by pressing a keyboard button twice. Subsequently, in a 4AFC procedure participants indicated the quadrant where the change occurred, whether they were aware of its location or not. The order between the temporal reproduction and the 4AFC task was counterbalanced between participants for possible effects in either of these tasks. Finally, participants had to respond, using two corresponding keyboard buttons, whether they had clearly perceived rectangle's displacement or not.
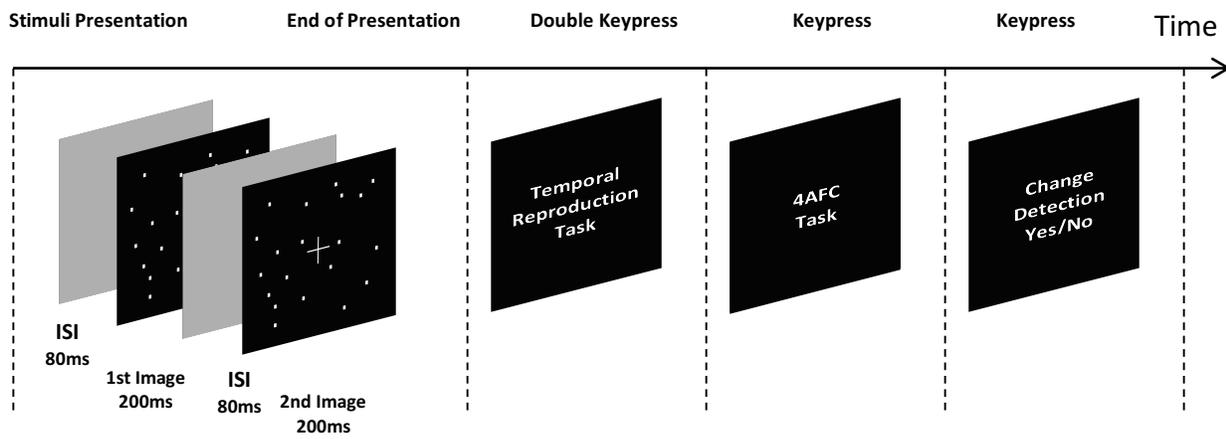
Figure 2. Schematic illustration of the flickering presentation and the following tasks in each trial.

Results

The data of nine participants was removed from the analysis because they could not execute all the parts of the procedure properly. For all the analyses in post-hoc comparisons, we used Bonferroni-corrected t-tests (where $p < 0.05$ prior to correction). In addition, we calculated

the coefficient of variation by dividing standard deviations with the corresponding mean reproductions for each condition.

We first analyzed how conscious change perception, complexity and time interval affected perceived duration. For that purpose, we analyzed the obtained data for perceived duration of 29 participants via a factorial repeated measures analysis of variance (ANOVA) with Complexity (2 levels: 20 and 30 rectangles), Interval (3 levels: short, medium, long) and Certainty (2 levels: yes, no) as the 3 within-subjects factors. The first two factors were manipulated by our experimental design, whereas the latter and its two related levels resulted from the categorization of participants' explicit response on whether or not they perceived the rectangle's positional change. The reproduced duration was regularized by dividing it with the corresponding temporal interval for each interval condition accordingly, in order to produce accuracy as the metric for interval's duration estimate. The analysis showed a significant main effect of interval's duration [$F(1.363,38.165)=43.087$, $p<0.001$, $\eta^2_p =0.761$] with short intervals (Mean accuracy=0.959) more overestimated as compared to medium (Mean accuracy =0.782) and long intervals (Mean accuracy=0.671), and the long intervals less overestimated as compared to medium intervals (see also Figure 3). The analysis did not reveal any significant main effect of either Complexity [$F(1,28)=0.074$, $p=0.787$, $\eta^2_p =0.003$] or Certainty [$F(1,28)=3.248$, $p=0.082$, $\eta^2_p =0.104$]. The interactions between Complexity and Interval [$F(1.539,43.080)=1.133$, $p=033.7$, $\eta^2_p =0.077$] and between Certainty and Interval [$F(1.568,43.917)=2.922$, $p=0.071$, $\eta^2_p =0.178$] did not also reached significance. However, post-hoc pairwise comparisons showed lower duration underestimation in Yes responses (M=0.996) than in No responses (M=0.922) for the short interval, with the greatest difference between yes and no responses found for the short interval in complexity level 20. We also obtained a significant interaction between Certainty and Complexity [$F(1,28)=5.776$, $p=0.023$, $\eta^2_p =0.171$], with lower underestimation for certainty yes (M=0.839) than certainty no responses (M=0.777) in complexity 20 but with no difference in accuracy between Yes and No certainty in complexity 30.
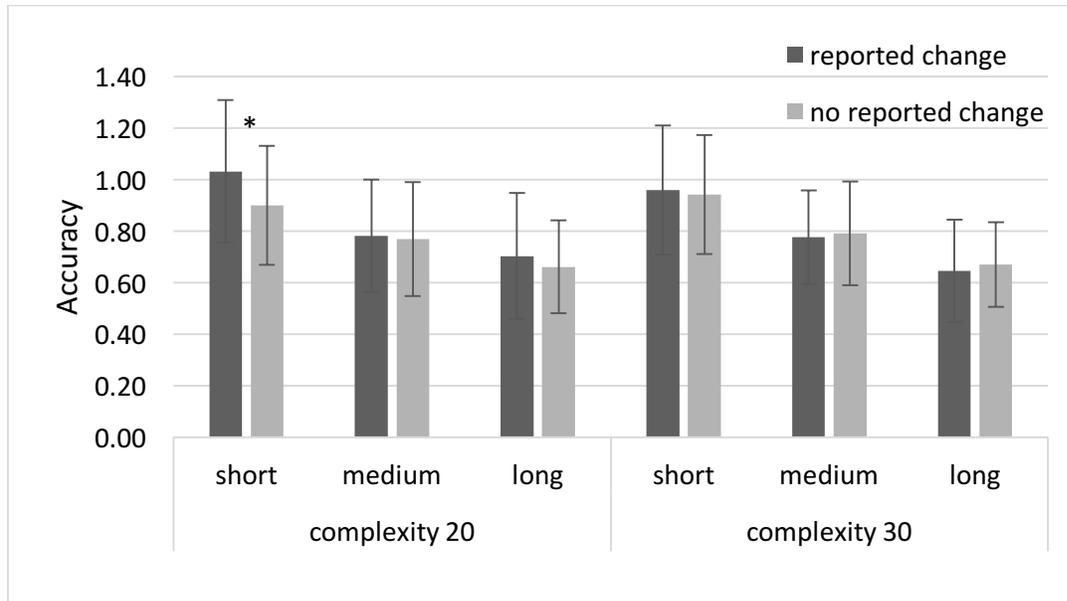
Figure 3. Temporal reproduction accuracy for every interval and complexity level of Exp. 1 and the comparison of judged duration between intervals with reported and no reported awareness of change. The asterisk indicates statistical significance p<0.05 for the pairwise comparison tests. The error bars represent the coefficient of variance.

In order to test for unconscious detection, we calculated, for each participant, the proportion of the sum of correct responses in the 4AFC task relative to the sum of no certainty responses (detection ratio; Chessman & Merikle, 1986; Fernandez-Duque & Thornton, 2000). We calculated this ratio on the aggregate set of responses, that is, irrespective of the experimental conditions, since no effect of Complexity [$F(1,15)=0.41$, $p=0.843$, $\eta^2_p=0.003$] or Interval [$F(2,14)=0.626$, $p=0.549$, $\eta^2_p=0.040$] on the detection ratio was revealed after the repeated measures ANOVA we performed. Seventy out of the 29 participants had detection ratio greater than 0.25, that is, above chance performance in a 4AFC task, indicating that 59% of participants detected unconsciously some changes. Using the data of those 17 participants, we performed a repeated measures ANOVA with Complexity, Interval, and Detection/Change as the within-subjects factors. Two levels of Detection/Change variable were formed after the categorization of the responses on the 4AFC when no awareness of change was reported. Under the level catch we summed the responses from the catch trials, that is, where no physical positional change occurred. The ANOVA revealed no significant main effect of Complexity

[F(1,15)=0.015, p=0.904, η^2_p=0.001] or Detection/Change [F(2,14)=1.867, p=0.191, η^2_p=0.211], but only a significant effect of Interval [F(2,14)=60.664, p<0.001, η^2_p=0.897] (see also Figure 4).
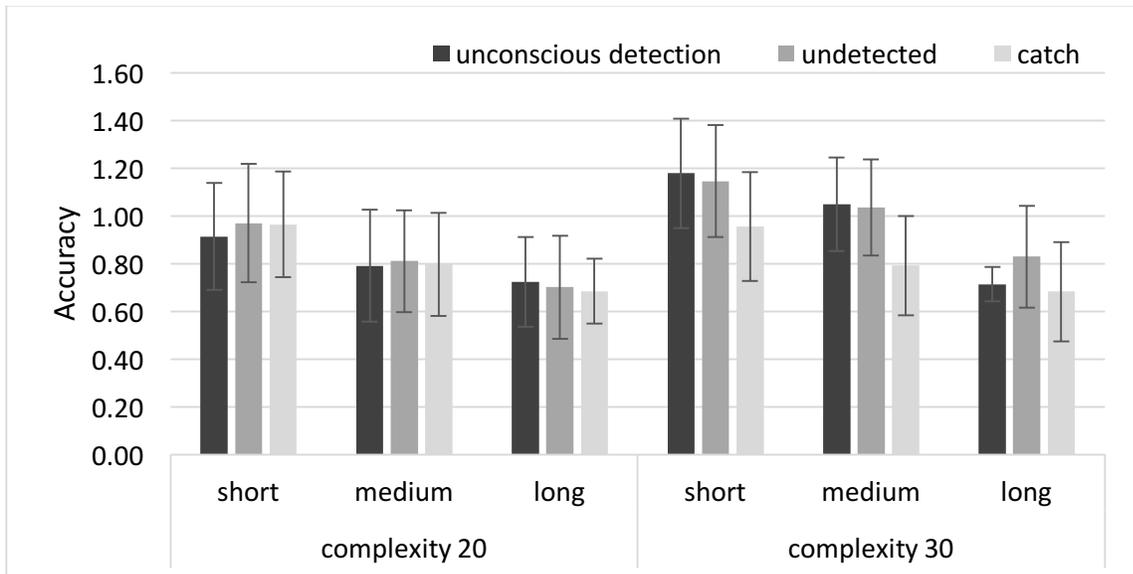
Figure 4. Temporal reproduction accuracy for every condition of Exp. 1 and for intervals without reported awareness of change and either correct response in the 4AFC task (unconscious change) or with false response (undetected change). Correct responses accounted for unconscious detection only for subjects with above chance level performance in the 4AFC task (>0.25). The error bars represent the coefficient of variance.

In order to examine the effect of change detection timing on perceived duration we estimated how detection time (or response time) correlates with accuracy. These correlation estimates (Pearson's r) are presented in Table 1, where we can observe that only for the long interval there was a significant, but low, negative correlation between detection time and accuracy. In order to further examine the role of detection time, we performed a repeated measures ANOVA with interval and complexity as within-subjects factors and detection time as the dependent variable. The analysis revealed an expected main effect of interval [F(2,20)=122.107, p<0.001, η^2_p=0.924], while no significant main effect of complexity was found [F(1,21)=3.890, p=0.062, η^2_p=0.156]. We also obtained significant interaction between complexity and interval [F(1.563,32.832)=4.055, p=0.33, η^2_p=0.289], where detection time for

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complexity 30 (M=2635 ms) was significantly lower than complexity 20 (M=2325 ms) only in the long interval (see Figure 5).
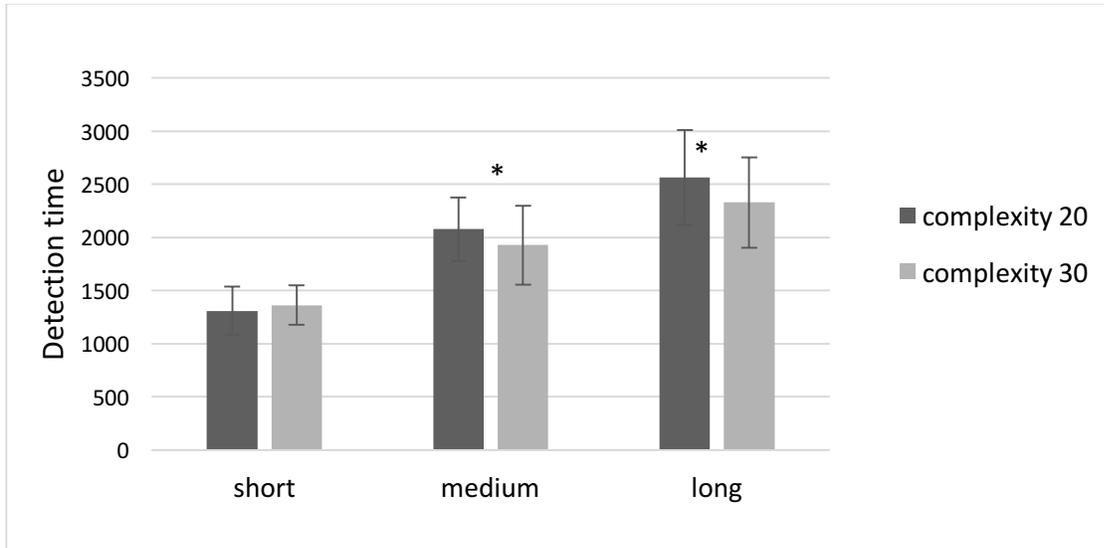
Figure 5. Mean detection time for every condition of Exp. 1. One asterisk indicates statistical significance p<0.05. The error bars represent standard deviations.

	short	medium	long
complexity 20	-0.08	-0.05	-0.24
complexity 30	0.06	-0.04	-0.22
total	-0.03	-0.07	-0.21

Table 1. Pearson's r correlation coefficient for the correlation between accuracy and detection time.

Discussion

The results from Experiment 1 do not provide any clear support to any of the three accounts on how change affects duration judgments. The effects, predicted from change-

saliency and the neural energy account, were not presented since no difference on accuracy was found between complexity levels for yes certainty. In addition, we did not find any main effect of Certainty on accuracy but only a main effect of Interval. Therefore, the main predictions of the number-of-change account were not fully confirmed. We also found no difference in accuracy measurements between unconsciously detected change, physical change, and absence of physical change suggests that either only change's awareness influences duration estimate or that the experimental design could not give rise to these effects. One possible explanation for the absence of a consistent effect of either conscious or unconscious change detection, or of other factors such as change's saliency, we assumed that may lie in procedure's difficulty in this demanding dual task. The obtained effect of Certainty on accuracy only for complexity 20 seems to support this explanation, since higher complexity certainly increases visual search difficulty in the detection task. Thus, as the high effect size of Interval on accuracy indicates as well, participants could have shaped their duration estimates mostly based on the frame's alternations. In addition, the fact that detection time was decreased with higher stimulus complexity possibly contrasts to our assumption that higher complexity rendered positional change less salient. It seems that the reduction of between-rectangle distance at the higher complexity level resulted in easier detection and presumably prompts the change's pop-out, despite the lower spatial selective attention. Thus, in our next experiment, we opted for a different stimulus manipulation that could provide a more reliable control on change's saliency. Regarding attention-related predictions, the negative correlation between accuracy and detection time only for the long interval was in partial support of the AGM assumptions since with earlier change's detection, a greater part of the interval duration could be devoted exclusively to the elapsed time as compared to later detection timing that does not allow for increased processing of temporal information. Negative correlation values where not found for the short interval, probably due to the very short period between change's detection and interval's end (less than 300 ms in most trials). However, the correlation values were not considerably high at the longer interval indicating that other factors or phenomena may have contributed to these duration judgments. Finally, the absence of a complexity effect on accuracy does not also follows the predictions of the Attention-based timing approach.

We attributed the absence of the predicted effects in Experiment 1 results to the high cognitive demands of the secondary task and the inability to optimally exploit stimulus manipulation to induce fully divergent effects on change's saliency and neural energy. Thus, in Experiment 2, we aimed to examine the same hypotheses as in Exp. 1 by introducing some changes to stimuli characteristics. Specifically, we decreased the difficulty of the detection task and manipulated the period of time stimuli images were presented relative to the overall interval's duration in order to modulate change's saliency and neural energy related to stimulus processing.

Experiment 2

In this experiment, we used the same apparatus and procedure as in Experiment 1 but with two changes in stimuli configuration. First, in order to decrease the difficulty of the detection task, we reduced the number of rectangles presented. And, second, we modulated postulated change's saliency and neural energy by modulating the ratio of main images' duration presentation (on-time) to ISI's duration (off-time). We hypothesized that the longer on-time (and the less off-time accordingly) would make change more predictable and, thus, less salient and hypothesized that this manipulation would evoke stronger neural responses for stimulus processing throughout interval's duration (Matthews, 2015; Matthews & Meck, 2016). Therefore, according to the change-saliency account longer on-time would lead to shorter duration judgments, while the neural energy account predicts that longer on-time would increase duration judgments. The predictions for the other timing accounts remain the same as hypothesized in Exp. 1.

Participants

Thirty-nine new participants took part in this experiment (26 females) aged between 18 and 37 years old (mean age = 21 years old).

Apparatus, Stimuli, Design, and Procedure

The stimuli differed from those of Exp1. in the following way: in each image for every condition they were 14 rectangles, and, thus, the detection task was less demanding. Additionally, we had two frame conditions: in one condition, on-time duration was 230ms (with

off-time 50ms), while in the other condition, it was 180ms (with off-time 100ms). The difference between these on-time image durations was added/subtracted to the off-time, that is to ISI duration, so that interval's duration among Frame levels to remain equal. In this experiment we removed the catch trials and we counterbalanced the order of the Frame block between participants. Apparatus and Procedure were identical to Exp.1.

Results

The data of eight participants were excluded from the analysis because they did not execute the whole procedure properly. We first performed a repeated measures ANOVA with Frame (on time: 230ms, 180ms), Interval (short, medium, long), and Certainty (2 levels: yes, no) as within-subjects factors. The analysis revealed a significant main effect of Interval [$F(1.327, 39.822)=78.026$, $p<0.001$, $\eta^2_p=0.722$] and Certainty [$F(1, 30)=4.779$, $p=0.037$, $\eta^2_p=0.137$] with perceived change intervals (M=1.02) being overestimated and intervals without change awareness underestimated (M=0.97). However, no significant main effect of Frame was obtained [$F(1, 30)=4.779$, $p=0.342$, $\eta^2_p=0.030$]. The interactions between Frame and Interval [$F(2, 29)=0.192$, $p=0.826$, $\eta^2_p=0.013$], Frame and Certainty [$F(1, 30)=0.144$, $p=0.707$, $\eta^2_p=0.005$], and Interval and Certainty [$F(1.728, 51.852)=0.902$, $p=0.417$, $\eta^2_p=0.059$] as well as the triple interaction [$F(2, 29)=0.289$, $p=0.751$, $\eta^2_p=0.020$] did not also reach significance.
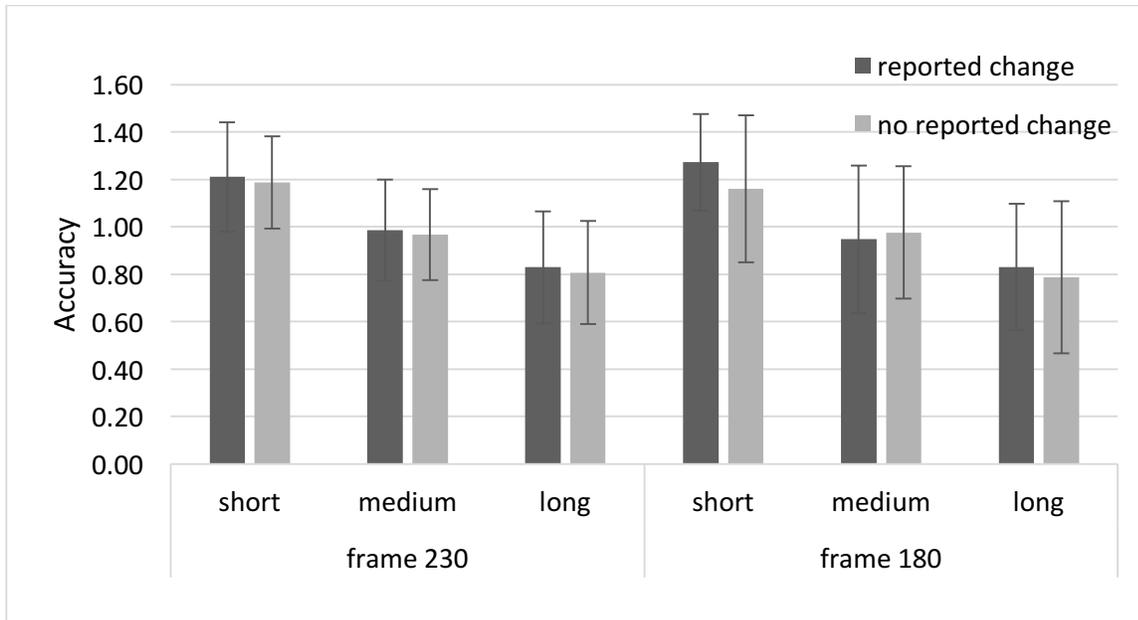
Figure 6. Temporal reproduction accuracy for every interval and frame's on-time level of Exp. 2 and the comparison of judged duration between intervals with reported and no reported awareness of change. The error bars represent the coefficient of variance.

Twenty-one of the thirty-one participants (68%) had above chance detection ratio in the 4AFC task. Using the data of those 21 participants, we performed a repeated measures ANOVA with Frame and Interval as the within-subjects factors and detection ratio in 4AFC as the dependent measure that did not revealed any significant main effect of Frame [$F(1, 20)=0.687$, $p=0.417$, $\eta^2_p=0.033$] or Interval [$F(2,19)=0.330$, $p=0.723$, $\eta^2_p=0.034$]. Subsequently, we performed a repeated measures ANOVA with Detection (2 levels: unconscious, undetected), Frame (2 levels: 230ms, 180ms), and Interval (3 levels: short, medium, long) as within-subjects factors and accuracy as the dependent variable. This analysis did not revealed any significant main effect of Detection [$F(1, 20)=0.467$, $p=0.502$, $\eta^2_p=0.023$], Frame [$F(1, 20)=2.304$, $p=0.245$, $\eta^2_p=0.103$], but only a main effect of Interval [$F(2, 19)=21.280$, $p<0.001$, $\eta^2_p=0.692$]. In addition, none of the interactions between Frame and Interval [$F(2, 19)=1.600$, $p=0.228$, $\eta^2_p=0.144$], Frame and Detection [$F(1, 20)=3.979$, $p=0.060$, $\eta^2_p=0.166$], or Interval and Detection [$F(2,19)=0,103$, $p=0.903$, $\eta^2_p=0.011$] reached significance.
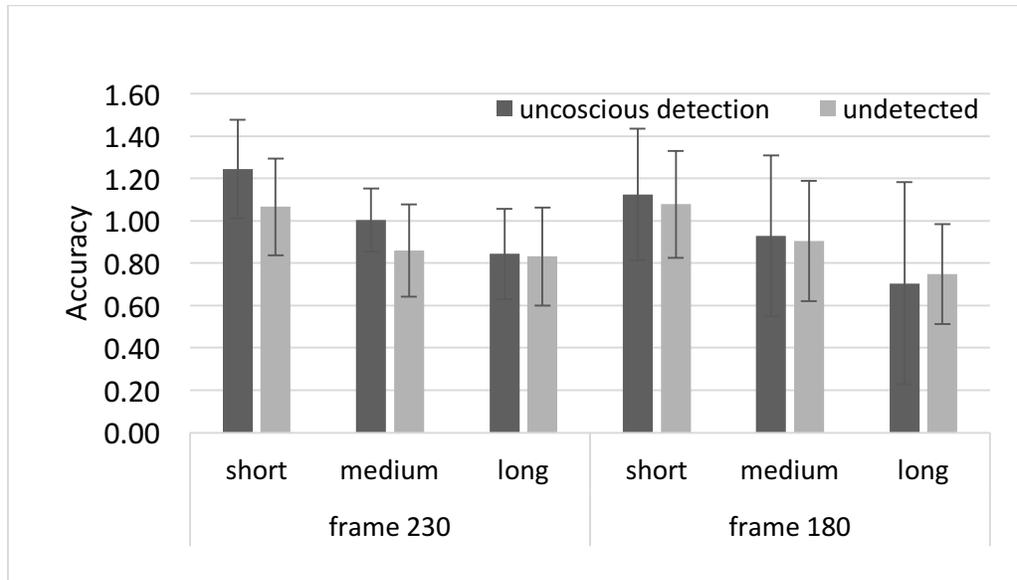
Figure 7. Temporal reproduction accuracy for every condition of Exp. 2 and for intervals without reported awareness of change and either correct response in the 4AFC task (unconscious change) or with false response (undetected change). Correct responses accounted for unconscious detection only for subjects with above chance level performance in the 4AFC task (>0.25). The error bars represent the coefficient of variance.

The coefficients of correlation we calculated between detection time and accuracy (as presented on Table 2) show that for the medium interval the two variables were negative correlated, while no correlation was found in the short and long interval (for the long one yet, the results suggest a trend of low negative correlation). To examine possible differences on detection time we conducted a repeated measures ANOVA with Frame and Interval as within-subjects factors. We obtained the expected main effect of Interval [$F(2,26)=117.422$, $p<0.001$, $\eta^2_p=0.900$], but no main effect of Frame [$F(1,27)=0,016$, $p=0.899$, $\eta^2_p=0.001$] or an interaction between Interval and Frame [$F(2,19)=0,103$, $p=0.903$, $\eta^2_p=0.011$] was obtained.
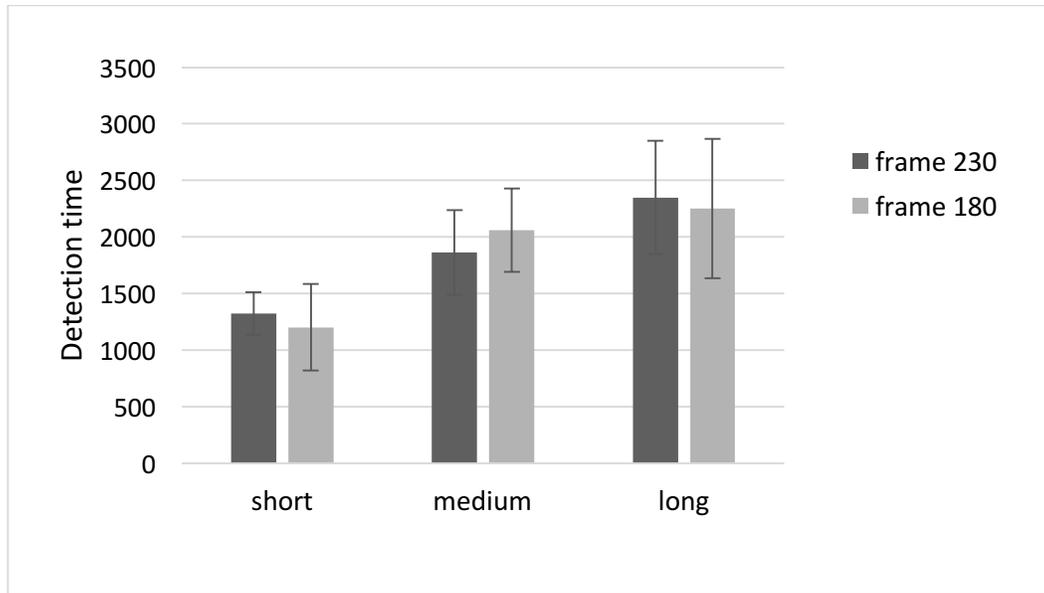
Figure 8. Mean detection time for every condition of Exp. 2. The error bars represent standard deviations.

	short	medium	long
frame 230	-0.06	-0.14	-0.10
frame 180	0.16	-0.34	-0.13
total	0.06	-0.20	-0.05

Table 2. Pearson's r correlation coefficient for the correlation between accuracy and detection time.

Discussion

Overall, the results from experiment 2 follow the predictions of the number-of-change account since intervals with report of change were followed by prolonged duration estimations relative to intervals with no reported change. In contrast, for yes certainty trials, frame's modulation had no impact on perceived duration and that evidence does not confirm the predictions of either the change-saliency or the neural energy account. The fact that accuracy for unconscious detection did not differ from accuracy when positional change was undetected confirms the hypothesis that only the awareness of detection could influence perceived

duration in any supra-second interval. Despite the fact that no change's saliency effect was found in Exp.2, it was not clear whether our main experimental set-up precludes the manifestation of such an effect or that the modification of a more prominent feature of change's appearance was required to elicit a change's saliency effect on perceived duration. In Experiment 3, therefore, we examined further whether or not the predictions of the change-saliency account could be met using a different stimulus manipulation to induce a differentiation of change's saliency. Specifically, in Exp. 3, we followed a more direct approach to modulate the phenomenal aspect of change by presenting rectangles of different colors, so that the color of the rectangle with positional change could vary.

Experiment 3

In this experiment, we exploited the fact that perceptual vividness varies among colors in order to produce changes of different saliency (Li, Xue, Tang, & Wu, 2014; Osberger & Rohaly, 2001). Previous studies have shown, either using subjective reports (Gelasa, Tomasic, & Ebrahimi, 2005) or behavioral measures (Li et al., 2014), that warm colors are perceived as more salient than cold ones, with red been regarded as the most vivid color and blue as the least vivid one. Based on these findings, instead of the white rectangles used in Exp. 2, in Exp. 3 we utilized red (highest visual vividness), green (medium visual vividness), and blue (lowest visual vividness) rectangles. Importantly, there are no statistically significant variations of neural responses (fMRI signal measurements) to different colors in areas specialized to color coding as shown in Brouwer and Hegger (2009). As a result from the above-mentioned findings, we could dissociate the effect of saliency and neural energy. Thus, if change saliency affects perceived duration, we expect higher duration estimate for the most salient colors, while the neural energy account predicts no differences to duration estimates when the color of the moving rectangle differs. The rest of the timing accounts provide the same predictions as described in Exps. 1 and 2.

Participants

Thirty-eight participants took part in experiment 3 (32 females) aged between 18 and 36 years old (mean age 21 years old).

Apparatus, Stimuli, Design, and Procedure

In this experiment, in each image 15 rectangles were presented, 5 red, 5 green, and 5 blue (see Figure 9), randomly distributed and with the same dimensions and brightness as in previous experiments. The tested colors were chosen from the CIELab color space (cf. Brouwer & Hegger, 2009; Gelasa, Tomasic, & Ebrahimi, 2005). For 30 trials the participants were presented with a red changing rectangle, for 30 trials with a green, and for 30 trials with a blue one. Thus, we had 90 trials in total where interval and color changed in each trial in a random intermixed fashion. We separated the trials in 2 blocks of 45 trials, where participants could take a break to rest for as long as they wanted. We also added a 3AFC task after the 4AFC task and before the detection task where participants had to report the color of the moving rectangle whether they had seen it or not. With this additional measurement we could assess potential effects of unconscious color detection on duration judgments. The rest of the apparatus, stimulus parameters, and procedure remained the same as in Exps. 1 and 2.
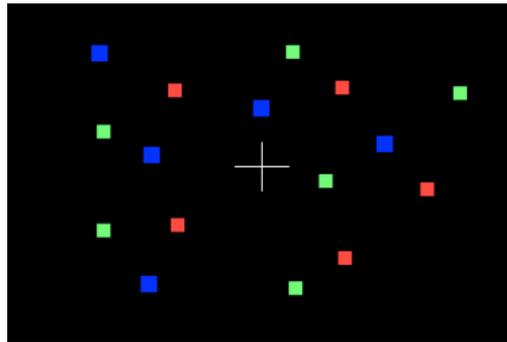
Figure 9. Stimuli image as presented in Exp. 3 with blue, green and red rectangles.

Results

The data of seven participants were removed from the analysis because they did not properly execute the whole procedure. A repeated measures ANOVA with Color (3 levels: red, green, blue), Interval (short, medium, long), and Certainty (2 levels: yes, no) as within-subjects factors was conducted. We obtained again a significant main effect of Interval [$F_{(1.300, 38.989)}=60.554$, $p<0.001$, $\eta^2_p=0.807$], while the main effect of Color [$F_{(2, 29)}=0.890$, $p=0.422$, $\eta^2_p=0.058$] and Certainty [$F_{(1,30)}=0.734$, $p=0.398$, $\eta^2_p=0.024$] did not reached significance (see also Figure 10). The interaction between Color and Certainty [$F_{(2, 29)}=0.425$, $p=0.658$,

η^2_p=0.029] and Color and Interval [F(2.969, 89.071)=1.425, p<0.256, η^2_p=0.173] were also not statistically significant. However, we did find a significant interaction between Interval and Certainty [F(1.643, 49.276)=5.646, p=0.008, η^2_p=0.280], with intervals of yes certainty (M=0.825) judged as longer than those of no certainty (M=0.775) but only for the long interval.
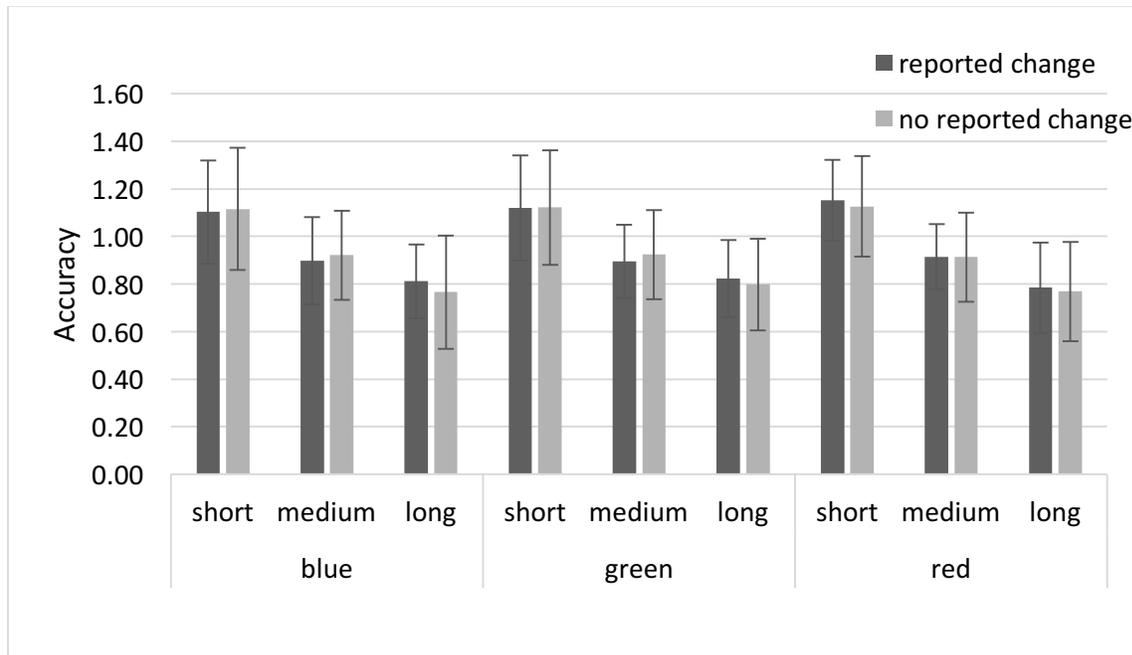
Figure 10. Temporal reproduction accuracy for every interval and complexity level of Exp. 1 and the comparison of judged duration between intervals with reported and no reported awareness of change. The error bars represent the coefficient of variance.

Twenty-six of the 31 participants (that is 84%) had detection ratio above 0.25 in the 4AFC. No significant main effect of Color [F(2, 31)=1.270, p=0.295, η^2_p=0.076] or Interval [F(2,31)=2.757, p=0.079, η^2_p=0.151] on detection ration was found. The accuracy data of those 26 participants were entered in a repeated measures ANOVA with Color, Interval, and Detection (unconscious detection, undetected). The analysis did not revealed any significant effect of Color [F(2, 24)=2.987, p=0.069, η^2_p=0.199] and Detection [F(1,25)=1.1781, p=0.194, η^2_p=0.067]. In addition, neither of the interactions between Color and Interval [F (4, 22)=0.098, p=0.982, η^2_p=0.018], Color and Detection [F(2, 24)=0.864, p=0.434, η^2_p=0.067], or Interval and Detection

[F(2,24)=0,761, p=0.478, η^2_p=0.060] reached significance. Only 17 of the 31 participants (55%), performed above chance level in the 3AFC, and for that reason we did not proceed to further calculations.
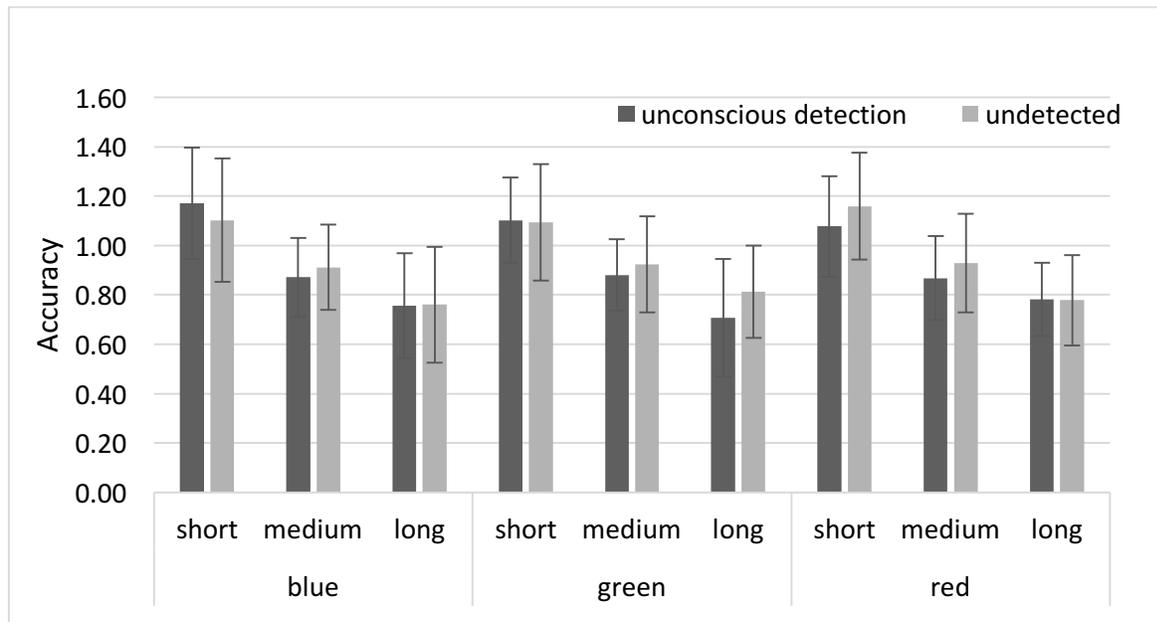
Figure 11. Mean accuracy of temporal reproduction for every condition of Exp. 3 and for intervals without reported awareness of change and either correct response in the 4AFC task (unconscious change) or with false response (undetected change). Correct responses accounted for unconscious detection only for subjects with above chance level performance in the 4AFC task (>0.25). The error bars represent the coefficient of variance.

Moreover, we calculated the correlation between detection time and accuracy (see Table 3) that showed no low positive correlation in the short interval, no correlation in the medium interval, and a low negative correlation in the long interval only for the red color, while no correlation was found for the other two colors. However, the within-subjects correlations between detection time and accuracy show that most of the participant presented negative correlations for every color in the long interval. We also examined possible differences on detection time by running a repeated measures ANOVA with Frame and Interval as within-subjects factors. We found the expected main effect of Interval [F(2,26)=170.503, p<0.001,

η^2_p=0.966], but we did no obtained a significant main effect of Color [$F_{(2,26)}$=0,073, p=0.930, η^2_p=0.012] or an interaction between Interval and Frame [$F_{(4,22)}$=0,221, p=0.920, η^2_p=0.081].
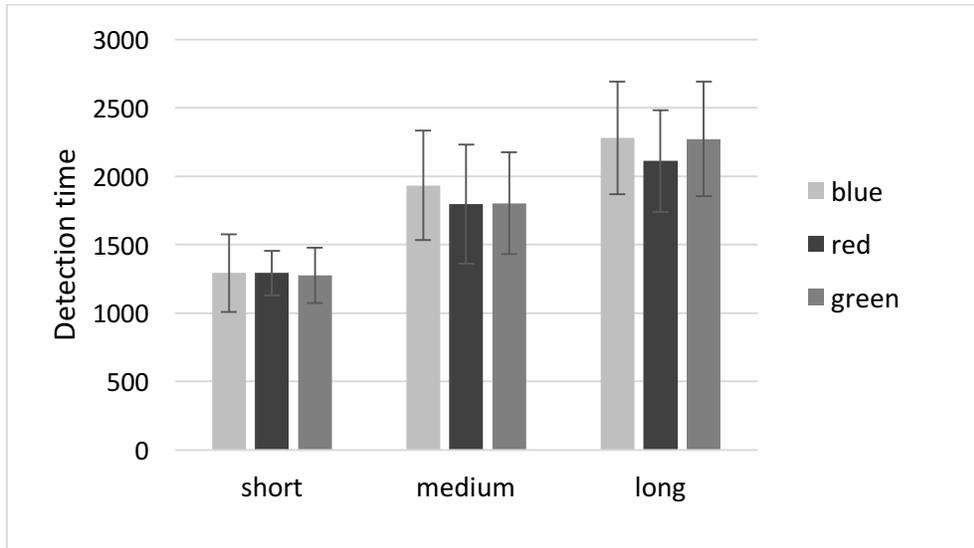
Figure 12. Mean detection time for every condition of Exp. 3. The error bars represent standard deviations.

	short	medium	long
blue	0.17	-0.12	0.11
red	-0.01	-0.04	-0.21
green	0.23	0.05	0.05
total	0.06	-0.05	-0.03

Table 2. Pearson's r correlation coefficient for the correlation between accuracy and detection time.

Discussion

The results from Exp. 3 showed that awareness of detection affects duration judgments only for the long interval as we found in Exp. 1 and, thus, do not support the number-of-change account assumptions. For trial with change's awareness, we found no difference in accuracy when the moving rectangle had different color. This finding seems in favor of the neural energy account and not the change-saliency account, however, the parameters of stimulus

presentation or procedure may have also hinder the emergence of multiple effects on duration judgments. In this experiment, we also confirmed the finding we obtain from exp. 1 and 2, that unconscious detection has no effect on duration estimates.

General Discussion

In this study, our primary aim was to investigate how visual changes affect the perceived duration of a time interval. Specifically, we attempted to answer whether perceived duration is mostly determined by the number of changes, the saliency of the change, or the neural energy expended to stimulus processing, while we also considered the role of change's awareness on experienced time. Additionally, we examined how attention modulates duration estimates both by regulating the allocation of cognitive resources between the temporal and non-temporal processing and according to the tasks' demands and the stimulus characteristics. We, thus, conducted three experiments, to test the three change-related timing accounts and the attention-related accounts, using a detection task and a time reproduction task. Most of the previous studies have interpreted time distortions of dynamic stimuli by considering either the number of changes or the neural resources devoted for their processing. Here, instead, we expected the subjectively perceived salience of the detected change to further influence duration judgments. Overall, the results of the three experiments did not fully meet the predictions of any of the main theoretical accounts. Nevertheless, the effect of consciously perceived change on duration judgments found in Experiment 1 and mostly in Experiment 2 are in favor of the number-of-change account, while unconscious detection did not affect perceived time in any experimental condition. In addition, manipulations of the neural energy related to the procession of the to-be-time interval and the salience of change did not yield significant effects on judged duration.

In Exp. 1, we manipulated stimulus complexity by differentiating the number of stimuli presented. In all conditions, the time interval's duration was underestimated, except from the short interval for Yes responses in the lowest complexity (i.e., 20). More importantly, we found awareness of change's detection to lengthen perceived duration only at intervals of complexity 20, but not those of the highest complexity level (i.e., 30). Increased stimulus complexity also did not induce greater duration judgments. By increasing the number of objects we increased

image's complexity and brightness and, as neurobiological findings have shown, greater number of presented stimuli or increased stimulus brightness is followed by extended neural responses (Barlow et al, 1978; Roitman et al., 2007; Tikhomirov et al. 1983). Nevertheless, we did not find any effect of the hypothesized neural energy variability, related to stimulus processing, on judged duration. One possible explanation could be that the complexity levels we used were either extremely high or with minor variation to induce a differential effect on judged duration. However, previous studies have also obtained similar results (Brown, 1995; Horr & Di Luca, 2015). Whereas behavioral studies have shown that numerosity and complexity influence judged duration of static stimuli (Folta-Schoofs, Wolf, Treue, & Schoofs, 2014; Xuan et al., 2007), the experimental manipulation of the number of dynamic objects has revealed mixed evidence regarding the effectiveness of numerosity to affect judged duration (Brown, 1995; Linares & Gorea, 2015). Linares and Gorea (2015) asked participants to estimate the duration of moving stimuli (ranging from 0.7 to 2.5 s) with the method of single stimuli. The stimuli used were either one or two blobs rotating on a circular trajectory where speed and radius were also manipulated. The number of stimuli was found to affect duration judgments since perceived duration was increased with the number of stimuli. On the contrary, the results of Brown's (1995) study manifest a different pattern. In his study, the number of linearly moving stimuli-targets (1, 3, and 5) and their speed (0, 10, and 30 cm/s) were manipulated. It was found that target numerosity affected duration judgments in a temporal production procedure only when targets were stationary, in contrast, when he used the same experimental manipulation in a temporal reproduction method no numerosity effect was revealed. In another experiment of this study aiming to further elucidate the effect of stimuli number on perceived duration, participants had to reproduce the duration of stimuli consisting of either 3 or 105 targets of speed motion ranging from 0 to 45 cm/s. The obtained results also showed that stimuli numerosity affected perceived duration only in the absence of motion. In general, the results of our first experiment seem in line with Brown's (1995), since we found that the number of dynamic objects does not influence the judged duration. These results expand the finding regarding the relationship between the numerosity of dynamic objects and their judged duration. In our study, the dynamic nature of our presented stimuli was due to flicker's

frequency and not due to their motion (either linear or circular) as in previous studies (Brown, 1995; Linares & Gorea, 1995). Thus, the results of Exp. 1 suggest that the temporal regularity produced by alternations of the whole visual field can consistently override the influence of numerosity or complexity on duration judgments. Finally, it's important to note that in Exp.1 numerosity, complexity, as well as image's brightness increased in parallel, thus, future studies need to dissociate these properties in order to examine which of them and how could affect the perceived duration of a dynamic stimulus.

In Exp. 2, we attempted to modulate change's saliency by modulating its predictability and the presentation time of object images relative to the blank images of ISI. In general, an unexpected or novel item appears more vivid and draws more attention than an expected or a recently presented one (Matthews, 2015; Matthews & Meck, 2016; Tse et al., 2004). We also hypothesized that by reducing stimulus complexity, we could facilitate the emergence of the expected effects, as it is indicated by the appearance of change's detection effect on judged duration only for the lower complexity level in Exp. 1. Indeed, in Exp. 2, we managed to obtain a main effect of conscious change detection on judged duration, however, frame's on-time manipulation had no effect. Prolonged duration of object's presentation interval is expected to increase the overall brightness of the interval and, thus, the magnitude of the relevant neural response (Eagleman & Pariyadath, 2009). In Exp.2, the assumed differentiation of neural response was not found to affect perceived duration yet. It is possible, though, that the reduced predictability for the interval with longer on-time frames could have produced an opposite to brightness neural response. Less expected stimuli usually trigger an alert response (Ulrich, Nitschke, & Rammsayer, 2006) or at least an increased allocation of cognitive resources for their processing (Tse et al., 2004), and this response could have a counter effect to neural processing to that we first hypothesized. Nevertheless, stimuli of greater brightness induce stronger stimulation to LGN (Tikhomirov, 1983) and primary visual cortex areas (Barlow, Snodderly & Shadlow, 1978), therefore, our results contest the assumption that the activity of neural populations that encodes low-level features reflects, in any case, stimulus perceived duration (Eagleman & Pariyadath, 2009). Therefore, future research on the relationship between neural activity and perceived duration should attempt to dissociate the effects of

stimulus manipulation on low-level and higher-level neural processing. Change's saliency also did not appear to affect perceived duration in Exp. 2. When an ISI increases, the temporal distance between the sequential appearances of the moving rectangle also increases. Therefore, we hypothesized that the manipulation of this temporal distance would result in varying expectation of rectangles apparent motion. Previous studies have manipulated expectation by altering either the frequency of objects appearance (Ulrich et al., 2006) or the extent of repetition (Tse et al., 2004) or high-level contextual factors (Cai, Eagleman, & Ma, 2015). It is, hence, possible that the manipulation we opted for in Exp. 2, since not being tested before, could not yield a strong saliency effect. Thus, further studies on the effects of stimulus saliency on perceived duration need to incorporate subjective reports of participants' perceptual impression in order to adequately assess phenomenal experience.

In Exp. 3, we manipulated the saliency of change by presenting rectangles of different colors that are known to have differential perceptual vividness (Gelasa, Tomasic, & Ebrahimi, 2005). However, this experimental manipulation did not provide the expected effect of change's saliency on perceived duration either. The non-significant variability of fMRI bold signal responses for the encoding of different colors seem to reflect this absence of influence of moving rectangles color on perceived duration (Brouwer & Hegger, 2009). However, in Exp. 3 conscious change detection did not influence duration judgments, except of a simple effect in the long time interval, where intervals without awareness of change detection were more underestimated relative to the judged duration of intervals of no witnessed change. Without any other new factor that could have hindered the emergence of the expected timing effects, it is plausible again the relationship between stimulus complexity and periodicity to have affected participants timing behavior. The number of objects (N=15) had a minor increase compared to those of Exp. 2 (N=14), however, color variation increased the amount of information in each image, and, thus, its complexity. More specifically, with stimuli of varying colors there is an additional perceptual dimension that differentiates presented stimuli, therefore, more chunks of information are required for the storage of an image in memory, resulting in higher total memory load, given that all other presentation parameters were identical. This fact combined with the added response regarding the color of the moving rectangle could have increased the

cognitive demands and the difficulty of Exp. 3. It is, nevertheless, possible that this manipulation did not also considerably modulated change's saliency, and thus, it was not sufficient to affect judged duration. Since detection time did not differ between color levels, it seems that different colors have not significantly varied saliency to differentially draw attention.

The findings of this thesis do not clearly support any of the three main theoretical accounts proposed here to address the role of change in perceived duration, that is, the number-of-change, the change salience, and the neural energy account. In Exp. 2, as well as in trials with stimulus complexity 20 in Exp. 1, we found that change detection lengthens intervals duration. On the contrary, in Exp. 3 and in trials with stimulus complexity 30 in Exp. 1, change detection did not affect duration judgments. Therefore, the positive linear relationship that the number-of-change account predicted was not ubiquitously found in our results, suggesting the modulatory role of other factors in interval timing besides the objective or perceived number of changes. Our findings are in line with those of previous studies that question that perceived duration is a function of the number of changes. Herbst et al. (2013) found that perceived duration decreases with increasing flicker, while Kanai et al. (2006) found that higher temporal frequency can induce time dilation up to a specific frequency (12 Hz). In addition, Matthews (2011) found that stimuli with constant speed are perceived as longer compared to stimuli with increasing or decreasing speed. Therefore, these findings and our results suggest that the judged duration of a time interval is not merely influenced by the number of perceived events during this period. Moreover, the results of Exp. 1 show that perceived duration is not related to the number of low-level changes neither, since in this manipulation stimulus complexity parallels the extent of changes encoded at early visual processing brain areas. The absence of an effect of sensory stimulation is also evident due to the fact that the duration of catch trial intervals (where there is no physical change) did not differ from judged duration of intervals where rectangle's change was completely undetected. These findings oppose previous studies, mostly in the subsecond range, that have indicated early sensory areas and low-level stimuli parameters as the primary sources of temporal information (Cai et al., 2015; Kanai et al. 2006).

Besides reported changes, we also assessed in a 4AFC task whether unconscious change detection could affect time estimates. In all experiments where participants performed above chance level in this detection task, we found that unconscious change detection does not influence judged duration. These results further support the conclusions derived from previous studies that also found that conscious perception (Herbst et al., 2013) and attentional selection (Herbst et al., 2012) are necessary for a perceived change to affect judged duration. Herbst et al. (2012) supported a 2-stage model for perception to explain how stimuli are perceived in the RSVP paradigm used in their study. In this model, change is at first perceived but fails to be registered in a post-perceptual level. On the other hand, in the change blindness we used, it has been supported that a change is not perceived unless attentional selection renders the representation of the specific visual area lasting and, thus, resulting in a stable registration of the change in memory (Rensink, 2000). In our paradigm, we provided a broad differentiation of the different level of stimulus processing, from physical stimulation to sensory stimulation of higher visual areas and from unconscious to conscious change detection. The method we used to assess unconscious detection is categorized as a subjective threshold method (Sandberg, Bibby, Timmermans, Cleeremans, Overgaard, 2011), and it has been mainly criticized on the ground that the subjectivity of the response criterion influences whether or not a perceived event is regarded as conscious. Thus, depending on how sensitive the criterion is, either some conscious percepts could be considered as unconscious or, conversely, unconscious processing could be gauged as conscious. In our study we asked participants to categorize a change's detection as a conscious event only when they had a fairly clear representation of the moving object. We opted for such a conservative criterion for two reasons: first, in order to avoid illusory motion percepts, created from stimuli afterimages due to the movement of eyes and head, to be considered as actual stimuli change, and, second, in order to implement a clear distinction between a plain phenomenal visual experience and perceived changes of partial awareness. It is possible, therefore, some vague but yet conscious changes to be classified as unconscious. We did not find, nonetheless, intervals duration with detected changes classified as unconscious to be judged differently relative to intervals duration with any kind of change detection. Thus, in the conditions of our study, perceived events with an impact on subsequent

behavior, as in the 4AFC task utilized here, should exhibit specific perceptual features to affect perceived time. Hence, the overall results of our experiments unequivocally indicate that only the awareness of detection can influence duration estimates, and especially when there is a definite perceptual experience of change. However, it is important to be further examined, using non-dichotomous classification of awareness, whether the varying degrees of events' conscious experience is reflected in subjective time estimates.

Our results, moreover, do not confirm the predictions of the neural energy account that assumes a parallel between the neural response evoked for the processing of a stimuli and its judged duration. Specifically, in Exp. 1 we did not obtain a positive relationship between complexity and perceived duration and neither a positive relationship between frame on-time and perceived duration in Exp. 2. The lack of differentiation of judged duration among the different colors of moving rectangles in Exp. 3 follows the predictions of the neural energy account as postulated by specific measures of brain activity on color encoding. However, the confirmation of the null hypothesis does not necessarily imply the validation of the neural energy account. Given that the lack of a color effect could result from various causes, and combined with the absence of the predicted effects in Exp. 1 and 2, we can infer that our overall findings do not support the neural energy account assumptions. Contrary to our study, most studies that confirm the predictions of the neural energy account have tested perceived duration in the subsecond time-scale (Eagleman & Pariyadath, 2009). However, it is not yet conclusive in this literature which measure of neural activity best reflects duration judgments, it is postulated though, that temporal information is mainly derived from computations of low-level stimulus characteristics (Cai et al., 2015; Kanai et al., 2006). In our study, we also correlated the magnitude of neural energy to low-level parameters (brightness) and to the attentional demands required within the to-be-judged interval. None of these experimental manipulations yielded a significant effect. The use of intervals in the suprasecond range may suggest that this account cannot be applied to examine perceived duration in this temporal scale. Future experimental designs should include both suprasecond and subsecond time intervals to elucidate the applicability of the neural energy account on any time-scale. Last, we

should notice that the lack of a direct measurement of neural activity is a significant restriction of our study to assess the theoretical predictions of the neural energy account.

The change-saliency account posits that the vividness of a stimulus influences its perceived duration. In Exp. 1 and Exp. 2 we attempted to manipulate in different ways the perceptual strength of the moving rectangle, while in Exp. 3 we used different colors to directly affect the visual qualities of the percept findings of our three experiments. However, none of these manipulations had an impact on duration judgments. In a recent review, Matthews and Meck (2015) introduced the processing principle to provide a unified explanation of how various factors influence perceived duration. The basic proposal of this principle was that "the subjective duration of a stimulus is positively related to the *strength* of its perceptual representation—the experienced vividness and clarity of the percept, and the ease with which information can be extracted from this representation". The effect of stimulus saliency on duration judgments was not addressed until Herbst et al.'s (2013) study. In that study, judged duration was found to be related to the subjective report of participants' impression of the light as a flickering stimulation. However, their predictions were formulated on the presumption that saliency would increase with increasing flickering frequency. Therefore, the initial predictions of the change-saliency account were also not confirmed in Herbst's et al. (2013) study. This divergence between expected, based on findings from previous studies, and reported saliency, indicates the sensitivity of this subjective measure to a vast number of stimulus configurations and presentation conditions. For this reason, perceived saliency could result from a combination of factors in unpredictable ways. Thus, supplementary subjective reports seem to be required to address the difficulty of evaluating phenomenal impression. Our experimental manipulations were probably met with the same issues. In our study, complexity manipulation appears not to have the expected effect on change's saliency and while predictability was not significantly differentiated in Exp. 2 between frame's levels, and thus the lack of saliency could be attributed to those reasons. Previous studies, nevertheless, have shown that warm colors are more vivid (Gelasa et al., 2005) and memorable (Kuhbandner et al., 2015) than cold ones and, thus, according to the "processing principle" we should have found an effect of color on duration judgments in Exp. 3. The fact that our change's saliency manipulations could not affect

perceived duration plausibly suggests that the assumptions of the change-saliency account, at least in our formulation, were not confirmed from our findings.

The inappropriateness our experimental manipulations to significantly differentiate the saliency of change is probably an important parameter for the lack of the presumed saliency effect. However, the fact that the flickering image provided a constant presentation of intense visual events, could explain why our attempts to differentiate the saliency of the detection event did not have the efficacy to produce any significant impact. Thus, a different approach to the notion of saliency could explain the pattern of our results. Poynter (1983) argued in his change-based account that change indexes the passage of time as the most salient event in the stream of consciousness. Hence, change segments the flow of time and structures experience in a way that is memorable and can subsequently affect retrospective duration estimates. Change could be, thus, considered as a critical perceptual parameter not in how affects the inferential procedure in timing computational processes, but in virtue of its perceptual phenomenological qualities. In this perspective, the significance of stimulus transformations is not only in the amount of changes within an interval but in the way they affect the whole flow and structure of experience. Previous studies have concluded that the critical parameter in a dynamic stimulus that mostly affects duration judgments is the one that most reliably conveys temporal information each time (Kaneko & Murakami, 2009; Linares & Gorea, 2015). In addition, Horr and Di Luca (2015) found that only the modulations of intervals' temporal regularity (isochronous vs asynchronous) had an impact on duration judgments but the changes of non-temporal stimulus regularity did not (due to modulations of fillers' sound amplitude or frequency). To inform our sense of the elapsed time, we receive and unify environmental, temporal and non-temporal, cues both at any one time, and over time. The above-mentioned findings suggest that the integration of these cues is performed in an optimal fashion, weighting more the events that provide a coherent temporal structure of the perceived interval. In our study, we also presented participants with various sources of temporal information and we found that duration judgments were affected by change detection only when they were aware of it and in conditions without considerably high non-temporal demands, while the other parameters did not affect perceived duration. The most reliable

temporal information in our paradigm could be obtained by the flickering of the whole image that provided a stable temporal structure composed of intense and predictably repeated visual events. In addition, each of three intervals we used was composed of a specific number of image repetitions. Thus, participants could easily relate each interval with a specific number of frames alternations, even though not explicitly, as they were asked not to. For these reasons, we assume that, in our experiment, the fact that the participants were presented with multiple temporal cues in a difficult dual task probably shaped their duration estimates mainly based on the flickering percept. The strong effect of Vierordt's law, as reflected on the effect size in the three experiments, strongly indicates that the actual duration of the time intervals was significantly related to their judged duration.

The importance of interval's temporal structure in timing and the way attention is allocated to specific time points has been previously emphasized by entrainment models of time, and especially by the Dynamic Attentional Theory (DAT; Jones & Boltz, 1989; McAuley & Jones, 2003). A central assumption of DAT is that attention, gradually, is tuned to the temporal regularities of the environment to provide an optimal distribution of cognitive resources and to obtain the better sensory signal of predictable events. Therefore, when periodically expected events are presented, attentional mechanisms prompt perceptual processing in specific periods and phases. In the stimulus presentation of our study, it is, thus, possible that the entrainment of attention to flicker's frequency to have also enhanced the effect of stimulus periodicity, by prioritizing the tracking of images' alternations. In this way, events without exhibiting this temporal regularity, as the detection of change, could be far less processed. Research findings have shown that this dynamic function of attention is supported by low-frequency (0.5 – 8 Hz) neural oscillations (Lakatos et al. 2008; Schroeder & Lakatos, 2009). These neural oscillations or the oscillating activity of other neural circuits (Buzsaki & Draguhn, 2004) have been proposed as the code of the temporal computations from entrainment timing models (Grondin, 2010; Henry & Hermann, 2014) while, certain pacemaker-accumulator models which, in general, rely on oscillatory operations, are also influenced by the entrainment to external events (Treisman et al., 1990; Ulrch et al., 2006). These models, therefore, can account for how the periodicity of our stimuli possibly was linked to, and provided, the implicit temporal code that produced the

subjective duration estimates. Thus, participants could reliably form interval's representation based on its temporal frequency, and this assumption further explains why other non-temporal factors could not elicit significant effects on judged duration.

We also examined the distribution of cognitive resources between the temporal and non-temporal tasks both as due to the allocation of attention in the dual task procedure and due to the variable difficulty of stimulus processing in the detection task. The predictions provided from the latter role of attention were not confirmed by our results since they are similar to those of the neural energy account. In order to assess how the distribution of attention between the detection and the timing task affect duration judgments, we measured the detection time correlates to reproduced duration. The results from the three experiments showed that in most conditions the correlation was very low (r<0.30), whereas, in general, we found negative correlation for the long interval and positive correlation only in some cases in the short interval. The fact that most of the highest correlation values were negative, supports the AGM that predicts longer perceived duration when participants detect the change earlier (Fortin & Masse, 2000; Zakay & Block, 1997). These findings also do not confirm the predictions of the attention-based account we hypothesized and indicates that it cannot be applied to explain duration judgments in dual task procedures. As previous studies also suggest, in dual task conditions, duration judgments could be best explained by the AGM assumptions (Block et al., 2010). Importantly, we have to note that in our study change's detection could influence perceived duration in two ways, with both of them producing the same effect. With change's detection, first, participants had more to time to attend to the lapse of time, and, additionally, they increased the registered number of events in memory. These two aspects of conscious change's detection both result in the expansion of subjective time. The effect size of detection's awareness in Exp.2 was $\eta^2_p=0.137$, whereas the average coefficient of correlation between detection time and accuracy is r =-0.08, so the coefficient of determination is $r^2=0.0016$. Since both η^2_p and r^2 are measures that show the extend of accuracy variance is explained away by each factor, it seems that only an insignificant part of change's detection is attributed to detection time. Finally, although we found mostly negative correlation values between detection time and accuracy that support AGM predictions, these values were very low, and,

thus, the effect of detection timing not as significant as in previous studies. This finding possibly indicates that the oscillations of attention due to stimulus entrainment could have primarily regulate the distribution of processing recourses more in temporarily regular fluctuations rather than with a constant allocation between temporal and non-temporal computations.

In conclusion, none of the three main timing accounts we examined could fully address our findings. The expected effect of saliency on duration judgments was not manifested in the results of our three experiments. However, to address these findings, we suggest a phenomenological approach that considers change as a salient event that provides the temporal structure of the stream of consciousness and indexes the elapsed time. Thus, we assume that when we encounter events that could provide temporal information of varying quality and when the perceptual and cognitive demands are high, then we rely more on periodical events to estimate the passage of time since time metrics are periodic in nature. In most of our results, it is evident that the judged duration of an interval is not a function of either the absolute number of changes or the neural energy required for the processing of its content. Differential attentional demands were also found to have a minor regulatory role, probably due to the periodic nature of the stimuli we used. An account that stresses the importance of stimulus saliency requires a definition of what saliency actually means that considers both objective and subjective measures. A saliency based account that relates the phenomenal characteristic of a fraction of experience with its perceived duration could provide a unified account of subjective time. A definite conclusion of our results was that perceived change has to fully reach awareness to influence time estimates. Finally, it is significant for future research to examine how and whether such a psychological account of saliency in time processing has a neural instantiation.

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