

Larger visual stimuli are perceived to last longer from time to time: The internal clock is not affected by nontemporal visual stimulus size

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Performance on interval timing is often explained by the assumption of an internal clock based on neural counting. According to this account, a neural pacemaker generates pulses, and the number of pulses relating to a physical time interval is recorded by a counter. Thus, the number of accumulated pulses is the internal representation of this interval. Several studies demonstrated that large visual stimuli are perceived to last longer than smaller ones presented for the same duration. The present study was designed to investigate whether nontemporal visual stimulus size directly affects the internal clock. For this purpose, a temporal reproduction task was applied. Sixty participants were randomly assigned to one of two experimental conditions with stimulus size being experimentally varied within either the target or the reproduction interval. A direct effect of nontemporal stimulus size on the pacemaker-counter system should become evident irrespective of whether stimulus size was experimentally varied within the target or the reproduction interval. An effect of nontemporal stimulus size on reproduced duration only occurred when stimulus size was varied during the target interval. This finding clearly argues against the notion that nontemporal visual stimulus size directly affects the internal clock. Furthermore, our findings ruled out a decisional bias as a possible cause of the observed differential effect of stimulus size on reproduced duration. Rather the effect of stimulus size appeared to originate from the memory stage of temporal information processing at which the timing signal from the pacemaker-counter component is encoded in reference memory.

Introduction

A number of psychophysical studies have demonstrated that large visual stimuli are perceived to last longer than smaller ones presented for the same duration in the subsecond range (e.g., Cantor & Thomas, 1976; Long & Beaton, 1980; Mo & Michalski, 1972; Thomas & Cantor, 1975, 1976). More recently, these findings were affirmed for longer durations ranging from 600 to 1800 ms (Rammsayer & Verner, 2014; Verner & Rammsayer, 2011; Xuan, Zhang, He, & Chen, 2007). Although the effect of nontemporal stimulus size on perceived duration can be considered a fairly well-established finding, it still remains unclear whether nontemporal stimulus size directly affects the processing of temporal information or merely biases decisions about duration (Yates, Loetscher, & Nicholls, 2012).

In time psychophysics, performance on time perception and duration discrimination in humans as well as time-related behavior in animals is often explained by the assumption of a hypothetical internal-clock mechanism based on neural counting (e.g., Creelman, 1962; Getty, 1975; Gibbon, 1977; Killeen & Weiss, 1987; Rammsayer & Ulrich, 2001; Simen, Rivest, Ludvig, Balci, & Killeen, 2013; Treisman, 1963, 2013). According to this account, a neural pacemaker generates pulses, and the number of pulses relating to a physical time interval is recorded by a counter. Thus, the number of pulses counted during a given time interval is the internal representation of this interval.

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As a consequence, the more pulses are counted during a given time interval, the longer its perceived duration.

From a theoretical perspective, there are several possibilities as to how pacemaker-counter models may account for the effect of nontemporal stimulus size on perceived duration. For example, nontemporal stimulus size could directly affect pacemaker rate. Several studies suggested a faster pacemaker speed due to increased arousal (e.g., Matthews, Stewart, & Wearden, 2011; Penton-Voak, Edwards, Percival, & Wearden, 1996; Treisman, Faulkner, Naish, & Brogan, 1990; Zelkind, 1973). On this view, a larger, compared to a smaller, nontemporal stimulus size may produce an increase in the subjective level of arousal and, thus, speed up the rate at which the pacemaker emits pulses, which, in turn, results in longer perceived duration.

An additional feature within the conceptual framework of pacemaker-counter models is a switch positioned between the pacemaker and the counter (Church, 1984). At stimulus onset, the switch closes and pulses flow into the counter; at stimulus offset, the flow of pulses stops as the switch opens again. If the latency to open and close the switch (i.e., the time taken to start and/or end the timing process) were affected by nontemporal stimulus size, this may also contribute to the effect of stimulus size on perceived duration. For example, if increased stimulus size leads to a shorter switch onset and/or a longer switch offset latency, then larger nontemporal stimulus size should result in a greater number of accumulated pulses and, thus, in a longer perceived duration compared to a smaller sized nontemporal stimulus of the same physical duration (cf. Wearden, Edwards, Fakhri, & Percival, 1998).

As an extension of the traditional pacemaker-counter models, Zakay and Block (1996, 1997) emphasized the crucial role of attention for perceived duration. Within the framework of their attentional-gate model, the pacemaker-counter mechanism is complemented by a gate mechanism. On their way to the counter, all pulses must pass through this gate, which is controlled by the amount of attentional resources allocated to temporal information processing. More specifically, the gate opens more widely or more frequently as more attention is paid to time and more pulses are transferred to the counter. Proceeding from the assumption that larger nontemporal stimulus size draws more attentional resources to the temporal stimulus information, it is conceivable that the attentional gate may open more widely. This may give rise to longer perceived duration due to a larger number of pulses accumulated during the time interval to be judged.

It should be noted that a mediating influence of arousal or attention on the effect of nontemporal stimulus size on perceived duration should become more pronounced with increasing physical duration (cf.

Matthews, 2011a; Penton-Voak et al., 1996). In contrast, however, the potential contribution of switch latency to the effect of nontemporal stimulus size on perceived duration would be independent of the physical duration of the interval to be judged (Matthews, 2011a). As a consequence, the relative effect of switch latency should decrease with increasing stimulus duration.

Altogether, the effect of nontemporal stimulus size could be explained within the conceptual framework of pacemaker-counter models. Although there are several plausible conceptions of how the effect of nontemporal stimulus size on perceived duration could be brought about, it still remains unclear whether this effect is, in fact, directly related to a type of timekeeping mechanism as specified by pacemaker-counter models. Alternative explanations of the effect of nontemporal stimulus size on perceived duration refer to more general cognitive mechanisms such as coding efficiency (e.g., Eagleman & Pariyadath, 2009; Pariyadath & Eagleman, 2007) or a generalized magnitude system (e.g., Conson, Cinque, Barbarulo, & Trojano, 2008; Srinivasan & Carey, 2010; Walsh, 2003). Most recently, the question has also been raised of whether nontemporal stimulus magnitude actually affects perceived duration of a stimulus or simply biases decisions about duration (Yates et al., 2012). Against this background, the present study was designed to investigate whether there is more direct experimental evidence for the notion that the effect of nontemporal stimulus size on perceived duration can be accounted for by an internal clock mechanism based on neural counting.

For this purpose, a temporal reproduction task was applied. In a typical reproduction task, the participant is required to reproduce a previously presented target duration by means of some operation (e.g., Grondin, 2008; Zakay, 1990). More specifically, the participant is first presented with a target interval. The internal temporal representation of this interval (i.e., the number of pulses counted during the target interval according to pacemaker-counter models) is then stored in reference memory in order to be subsequently reproduced. The reproduced duration is assumed to be based on a comparison between the number of pulses counted during the reproduction interval and the internal representation of the target interval stored in memory (Baudoin, Vanneste, Pouthas, & Isingrini, 2006; Franssen & Vandierendonck, 2002; Kargerer, Wittmann, Szlag, & von Steinbüchel, 2002; Mioni, Stablum, McClintock, & Grondin, 2014; Zakay & Block, 1997). If the number of pulses registered during the reproduction interval matches the one of the target interval, the participant terminates the reproduction interval by a motor action such as pushing a button.

Thus, a general prediction of pacemaker-counter models is that with regard to temporal reproduction the

duration of both the target as well as the reproduction interval can be considered a function of the number of pulses accumulated during each interval. This assumption implies that a direct effect of nontemporal stimulus size on perceived duration should become evident in the temporal reproduction task regardless of whether nontemporal stimulus size was experimentally varied within the target or the reproduction interval.

When the duration of the target interval is marked by either a physically small or large stimulus and, at the same time, the size of the stimulus indicating the reproduction interval remains constant across all trials, then the reproduced duration should be longer for the larger than for the smaller nontemporal stimulus size. This is because, in the reproduction phase, it takes more time until the higher pulse count will be reached that had been encoded during the target interval when the larger stimulus was presented. On the other hand, when the target interval is indicated by a stimulus of constant nontemporal size and in the reproduction interval either a small or a large stimulus is presented, then the initial pulse count encoded during the target interval should be reached faster and, thus, lead to shorter reproductions in the case of a larger compared to a smaller nontemporal stimulus size. If these predictions hold, a larger stimulus presented in the target interval should result in longer perceived duration, indicated by longer reproduced durations, than a smaller stimulus. On the other hand, a larger stimulus presented in the reproduction interval should yield longer perceived duration and, thus, lead to a shorter reproduction of the target interval. Hence, if it is correct that stimulus size affects perceived duration by directly affecting the number of pulses, then a statistically significant interaction between stimulus size (small or large stimuli) and manipulation interval (experimental variation of nontemporal stimulus size in the target or in the reproduction interval) should be the expected outcome.

There are at least three different methods commonly employed for reproducing time intervals (Mioni et al., 2014). In Method 1, the participant is required to hold down a button to reproduce the target duration. For Method 2, the participant pushes a button to start and stop the reproduction, whereas for Method 3, the participant just has to stop the reproduction interval by a keypress. In a recent psychophysical study, Method 3 was shown to be better suited than Methods 1 and 2 for the reproduction of brief intervals in the 1-s range (Mioni et al., 2014). Furthermore, when participants are asked to judge the duration of an interval, many of them adopt a counting strategy. It has been established that explicit counting becomes a useful timing strategy for intervals longer than approximately 1200 ms (Grondin, Meilleur-Wells, & Lachance, 1999; Grondin, Ouellet, & Roussel, 2004). Based on these consider-

ations, for the present study, the longest target duration was chosen not to exceed this critical value and a temporal reproduction task was employed that required only a keypress to end the reproduction.

Within the context of a timing task, nontemporal stimulus size represents an irrelevant stimulus dimension. To date, it is not known whether nontemporal stimulus magnitude has to be processed consciously to effectively influence perceived duration (cf. Xuan et al., 2007; Yates et al., 2012). Furthermore, it may be that the salience of nontemporal stimulus size may differ depending on whether the experimental manipulation of stimulus size takes place either during the target or during the reproduction interval (cf. Brown, 1997; Matthews, 2011b). Therefore, to identify a possible intervening effect of stimulus salience or attention, a dual-task paradigm was applied in the present study. In addition to temporal reproduction as the primary task, a secondary task was added where salience of nontemporal stimulus size was experimentally varied. In the salience condition, participants were required to pay special attention and to explicitly process nontemporal stimulus-size-related information, whereas in the control condition, nontemporal stimulus size was introduced as an irrelevant stimulus feature. This was achieved by prompting the participants to focus their attention on stimulus shape.

Method

Participants

The participants were six male and 54 female adult volunteers ranging in age from 18 to 43 years (mean age \pm SD: 22.4 ± 3.88 years). Participants were randomly assigned to one of two experimental conditions (i.e., experimental variation of nontemporal stimulus size within either the target or the reproduction interval) with the restriction that male and female participants were evenly divided between the two conditions. All participants were undergraduate psychology students and received course credit for taking part in this study. They were naive about the purpose of this study and had normal or corrected-to-normal vision. The study was approved by the local ethics committee and informed consent was obtained from each participant prior to the experiment.

Stimuli and procedure

The presentation of stimuli was controlled by E-Prime 2.0 experimental software (Psychology Software Tools, Inc., Sharpsburg, PA) running on a Dell

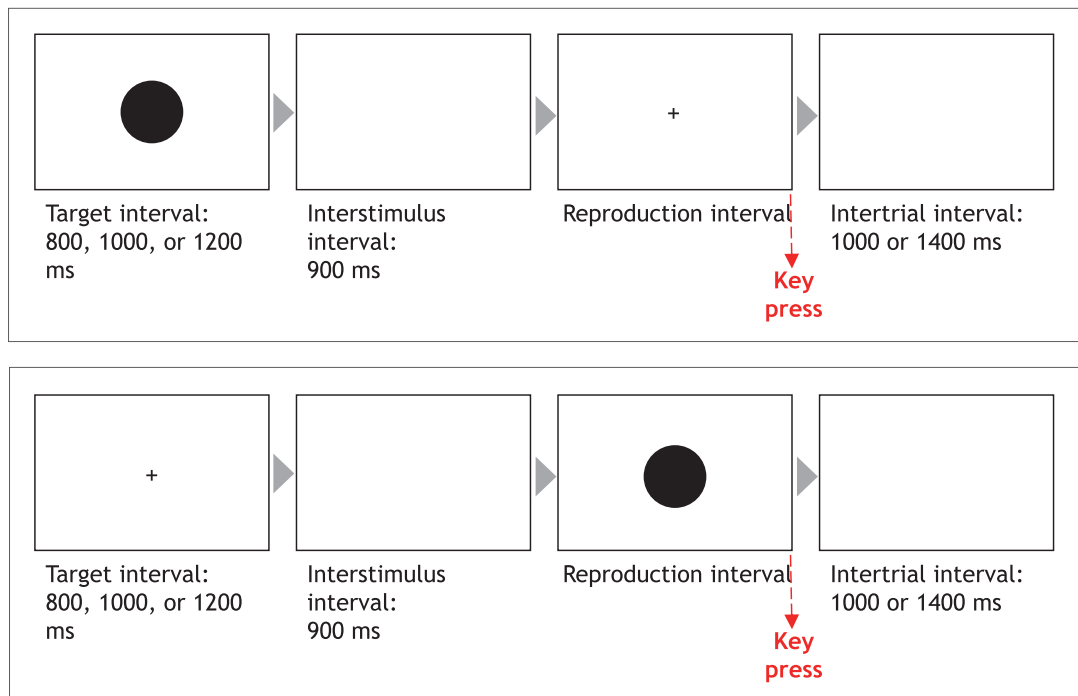


Figure 1. A sample trial of the temporal reproduction task with nontemporal stimulus size experimentally varied within the target interval (upper panel) or within the reproduction interval (lower panel). In the upper panel, the target interval consists of a large filled circle presented for either 800, 1000, or 1200 ms. After a 900-ms interstimulus interval (blank screen), the reproduction interval marked by a fixation cross was started. The participant terminated the reproduction interval by pressing a designated response button when he/she perceived the reproduction interval as temporally identical to the immediately preceding target interval. The next trial began after an intertrial interval of either 1000 or 1400 ms. In the lower panel, the target duration is indicated by the presentation of a fixation cross, whereas the reproduction interval is marked by a large filled circle.

Optiplex 760 computer (Dell, Inc., Round Rock, TX) connected to a 17-in. monitor (Samsung SyncMaster 172N, Samsung Electronics, Seoul, South Korea) with a vertical refresh rate of 75 Hz. Participants' responses were logged by means of a Cedrus RB-730 response box (Cedrus Corporation, San Pedro, CA). For experimental variation of nontemporal stimulus size, either filled squares or filled circles were presented in two different sizes subtending a visual angle of 1.2° and 10.0° , respectively. In the interval with no experimental manipulation of stimulus size, a fixation cross of a constant size subtending a visual angle of 2.0° was presented. All stimuli were presented in black color on a white background at a viewing distance of 60 cm.

In the experimental condition where nontemporal stimulus size was varied within the target interval, each participant performed two versions of the reproduction task conforming to the salience and the control condition, respectively. Order of version was balanced across participants. On each version of the task, the participant was required to reproduce three different target intervals. Durations of the target intervals were 800, 1000, and 1200 ms. There were 16 presentations of each target duration resulting in a total of 48 trials for each version of the task. The 16 presentations of each

target duration consisted of four trials of each of the four possible factorial combination of stimulus shape (circles and squares) and stimulus size (small and large). All 48 trials were presented in random order. On each trial, the target interval was followed by a blank screen for 900 ms. The start of the reproduction interval was marked by the appearance of a fixation cross. Participants were instructed to end the reproduction interval by a keypress when its duration was perceived as temporally identical to the corresponding target interval. After termination of the reproduction interval, a blank screen was presented for either 1000 or 1400 ms before the next trial was started. These two intertrial intervals were presented in randomized order to prevent a rhythmic response pattern.

In the experimental condition where nontemporal stimulus size was experimentally varied within the reproduction interval, the procedure was exactly the same, except that the three target durations (800, 1000, and 1200 ms) were marked by the fixation cross, whereas the reproduction interval was indicated by either circles or squares of two different sizes (see Figure 1).

In addition to the temporal reproduction task, participants were required to indicate whether the

	Target duration					
	800 ms		1000 ms		1200 ms	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Stimulus size						
Small	937	150	1049	147	1150	167
Large	940	157	1076	175	1185	171
Stimulus attribute relevance						
Low	934	161	1064	165	1159	159
High	944	160	1062	170	1177	184
Manipulation interval						
Target interval	879	139	1046	156	1181	163
Reproduction interval	999	138	1079	158	1155	167

Table 1. Means (*M*) and standard deviations (*SD*) of reproduced durations as a function of target duration, nontemporal stimulus size, stimulus salience, and manipulation interval. *Note.* All data in ms.

stimulus that varied in size was either small or large (salience condition) or whether it was a circle or a square (control condition). More precisely, in the salience condition, participants had to press one of two designated response buttons in order to terminate the reproduction interval if the stimulus varying in size was small and the other one if a large stimulus was displayed. In the control condition, stimulus size was irrelevant and response buttons corresponded to the geometrical shape (circle or square) of the stimulus. The assignment of response button to hand was held constant within each participant but was balanced across participants.

On each trial, the reproduced duration was logged with an accuracy of ± 1 ms. As a quantitative measure of perceived duration, mean reproduced durations (MRDs) were computed for each experimental condition. The effect of stimulus size on perceived duration was defined as the difference between the MRD for the large stimulus size and the corresponding MRD for the small stimulus size.

Results

To control for outliers, a procedure based on the one suggested by Chang, Tzeng, Hung, and Wu (2011) was applied. At first, for each participant, all reproduced durations that were more than ± 2 *SDs* from that participant's MRD for a given target interval were considered invalid trials and, thus, not included in further data analysis. By using this criterion, less than 4% of all trials were removed from data analysis. In a next step, each participant's remaining reproduced durations were submitted to a one-way analysis of variance (ANOVA) with target intervals (800, 1000,

and 1200 ms) as three levels of a repeated-measurement factor. The lack of a significant main effect of target duration on reproduced durations would imply an individual's inability to follow the instruction to reproduce the target intervals. None of our participants had to be excluded on the basis of this latter criterion.

Analysis of error rates on the two versions of the secondary task yielded faultless performance and, thus, indicated that all participants conformed to the instructions of the salience and control condition, respectively. There also was no indication of a statistically significant effect of stimulus shape (circles and squares) on MRD. Therefore, for further statistical analyses, data were collapsed across shapes of stimuli. Means and standard deviations for reproduced durations as a function of target duration, nontemporal stimulus size, stimulus salience, and manipulation interval are given in Table 1.

In a next step, a four-way ANOVA was performed with Target Duration (800, 1000, and 1200 ms), Stimulus Size (small and large stimuli), and Stimulus Attribute Relevance (salience and control condition) as three repeated-measurement factors, and Manipulation Interval (manipulation of stimulus size either within the target interval or within the reproduction interval) as a between-subjects factor. To protect against violations of sphericity, Greenhouse-Geisser corrected *p* values are reported where appropriate (cf. Geisser & Greenhouse, 1958).

Analysis of variance revealed statistically significant main effects of Target Duration, $F(2, 116) = 310.92$, $p < 0.001$, $\eta_p^2 = 0.843$, and Stimulus Size, $F(1, 58) = 11.32$, $p < 0.01$, $\eta_p^2 = 0.163$. The significant main effect of Target Duration indicated longer MRDs with increasing duration of the target interval; MRDs (\pm *SD*) were 939 ± 150 ms for the 800-ms target duration, 1063 ± 157 ms for the 1000-ms target duration, and 1168 ± 164 ms for the 1200-ms target duration. A post hoc Scheffé test showed that MRDs of all three target durations differed significantly from each other ($p < 0.001$). The significant main effect of Stimulus Size on MRD clearly argued for an effect of nontemporal stimulus magnitude on perceived duration. Large stimuli were reproduced longer than small stimuli; MRDs were 1045 ± 146 ms and 1067 ± 155 ms for small and large stimuli, respectively. There was no main effect of Stimulus Attribute Relevance on MRD, $F(1, 58) = 0.47$, $p = 0.49$, $\eta_p^2 = 0.008$; MRDs for the salience and control condition were 1052 ± 152 ms and 1061 ± 161 ms, respectively. Also no main effect of Manipulation Interval on MRD could be established, $F(1, 58) = 1.24$, $p = 0.27$, $\eta_p^2 = 0.021$; MRDs were 1035 ± 147 ms and 1078 ± 150 ms when nontemporal stimulus size was experimentally varied during presentation of the target and reproduction stimulus, respectively.

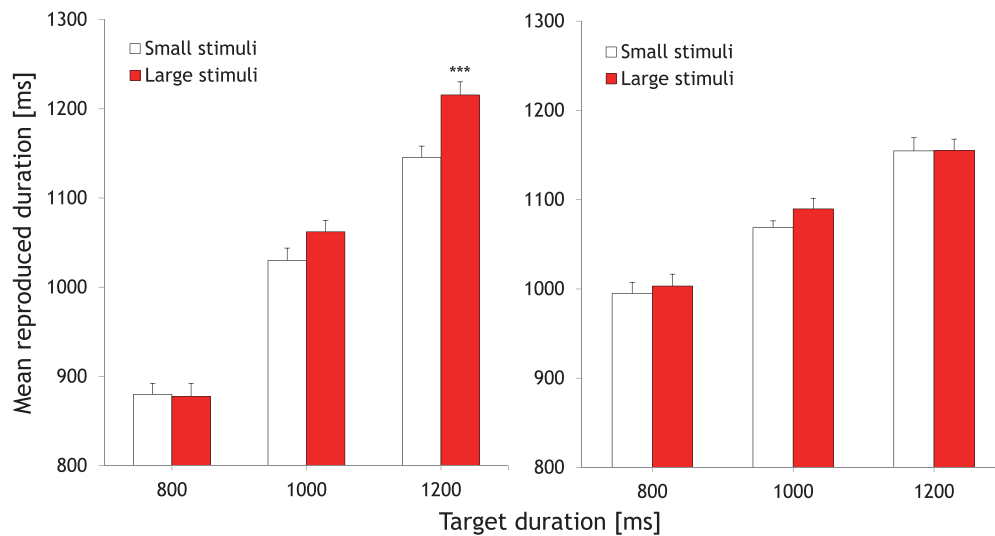


Figure 2. Reproduced duration as a function of stimulus size and target duration when stimulus size was varied during the target (left panel) or the reproduction interval (right panel). An effect of stimulus size on reproduced duration could be established only when stimulus size was varied during the target interval. This effect was effectively moderated by the duration of the target interval. A Scheffé post hoc test revealed a statistically significant longer reproduced duration with large compared to small stimulus size for the 1200-ms target interval. Error bars: 95% confidence interval calculated as recommended by Baguley (2012). *** $p < 0.001$.

Statistically significant two-way interactions were revealed for Target Duration and Stimulus Size, $F(2, 58) = 4.11$, $p < 0.05$, $\eta_p^2 = 0.066$, as well as for Target Duration and Manipulation Interval, $F(2, 116) = 31.93$, $p < 0.001$, $\eta_p^2 = 0.355$. It is particularly important to point out that the interaction between Stimulus Size and Manipulation Interval failed to reach statistical significance, $F(1, 58) = 3.27$, $p = 0.08$, $\eta_p^2 = 0.053$. This finding argues against the general notion that stimulus size affects perceived duration by directly affecting the number of pulses. However, a significant three-way interaction of those three factors combined, $F(2, 116) = 6.32$, $p < 0.01$, $\eta_p^2 = 0.098$, provided evidence for a mutual interference among Stimulus Size, Target Duration, and Manipulation Interval. No other interactions reached the 5% level of statistical significance.

An additional analysis was performed to assess the significant three-way interaction among Stimulus Size, Target Duration, and Manipulation Interval more thoroughly. For this purpose, two-way ANOVA with Stimulus Size and Target Duration as repeated-measurement factors were conducted separately for experimental manipulation of the nontemporal stimulus size during the target interval and the reproduction interval, respectively.

When nontemporal stimulus size was experimentally varied during presentation of the target duration, significant main effects of Target Duration, $F(2, 58) = 257.21$, $p < 0.001$, $\eta_p^2 = 0.899$, and Stimulus Size, $F(1, 29) = 11.00$, $p < 0.01$, $\eta_p^2 = 0.275$, could be observed. Averaged across all three target durations, MRDs were 1019 ± 142 ms and 1052 ± 157 ms for small and large

stimuli, respectively. Also the interaction of both these factors became statistically significant, $F(2, 58) = 8.91$, $p < 0.001$, $\eta_p^2 = 0.235$. Subsequent Scheffé post hoc analyses revealed a reliable effect of stimulus size on MRD for the 1200-ms target durations ($p < 0.001$), but not for the 1000- and 800-ms target durations. As can be seen from Figure 2 (left panel), with the 1200-ms target duration, the larger stimulus size resulted in significantly longer reproduced durations than the small one; MRDs were 1216 ± 168 ms and 1146 ± 166 ms for large and small stimuli, respectively.

When nontemporal stimulus size was experimentally varied during the reproduction interval, the significant main effect of Target Duration remained statistically significant, $F(2, 58) = 76.03$, $p < 0.001$, $\eta_p^2 = 0.724$. However, neither a significant main effect of Stimulus Size, $F(1, 29) = 1.55$, $p = 0.22$, $\eta_p^2 = 0.051$, nor a significant interaction of Target Duration and Stimulus Size, $F(2, 58) = 0.85$, $p = 0.43$, $\eta_p^2 = 0.028$, was found in this latter condition. In fact, there was no indication of an effect of stimulus size even for the longest target duration (see Figure 2, right panel).

The overall pattern of results obtained in the present study clearly indicated that an effect of nontemporal stimulus size on reproduced duration can be observed only if stimulus size is varied during the target interval. During the reproduction interval, an increase in nontemporal stimulus size had no effect on reproduced durations. Furthermore, if there was an effect of stimulus size on reproduced duration, this effect was more pronounced for longer than for shorter target durations. Finally, the absence of a statistically

significant main effect of stimulus attribute relevance or any statistically significant interactions including stimulus attribute relevance argued against a direct or a possible intervening effect of attention paid to stimulus size on MRD.

Discussion

The primary goal of the present study was to investigate whether the effect of nontemporal stimulus size on perceived duration can be accounted for by an internal clock based on neural counting. For this purpose, a temporal reproduction task was applied. With this psychophysical task, a direct effect of nontemporal stimulus size on the pacemaker-counter component of the internal clock should become evident by a statistically significant interaction between stimulus size and manipulation interval. To be more specific, a larger stimulus presented during the target interval should result in a longer reproduced duration, whereas a larger stimulus presented in the reproduction interval should yield a shorter reproduced duration as compared to a small stimulus.

When stimulus size was experimentally varied during the target interval, a positive effect of nontemporal stimulus size on reproduced duration could be observed. On average, large stimuli presented at durations ranging from 800 to 1200 ms were reproduced approximately 3.2% longer than small stimuli presented for the same durations. This effect of nontemporal stimulus size on reproduced duration, however, was found to be effectively modulated by target duration and became statistically significant for the 1200-ms target duration only. At this latter target duration, the large stimuli were reproduced 6.1% longer than the small ones. On the other hand, experimental variation of nontemporal stimulus size during the reproduction interval turned out to have no effect on reproduced duration irrespective of the target duration. In addition, the complete absence of any effect associated with stimulus attribute relevance indicates that the observed differential effect of nontemporal stimulus size on reproduced duration was not caused by a potential difference in attention paid to small and large nontemporal stimuli during the target and the reproduction interval, respectively. This latter outcome is consistent with Xuan et al.'s (2007) notion that nontemporal stimulus magnitude does not have to be processed intentionally to effectively influence perceived duration.

The fact that an effect of nontemporal stimulus size on reproduced duration could be established only when stimulus size was experimentally varied during the target duration clearly argues against the notion of an direct effect of nontemporal stimulus size on the

pacemaker-counter component as the core feature of neural counting models. If the effective number of pulses accumulated in the counter were indeed influenced by nontemporal stimulus size, an effect of stimulus size should have become evident for both the target and the reproduction interval. This is because within the conceptual framework of neural counting models, the internal representations of both the target and the reproduced duration are considered a direct function of the number of pulses registered by the counter (Baudoin et al., 2006; Franssen & Vandierendonck, 2002; Karger et al., 2002; Mioni et al., 2014; Zakay & Block, 1997). Furthermore, the observed differential effect of nontemporal stimulus size on reproduced duration implies that neither an arousal-induced increase in pacemaker rate (cf. Matthews et al., 2011; Penton-Voak et al., 1996; Treisman et al., 1990) nor a larger pulse count due to a more open attentional gate (cf. Zakay & Block, 1996, 1997) or changes in switch latencies (cf. Wearden et al., 1998) can account for the longer reproduced duration elicited by larger stimuli presented during the target interval.

Besides a pacemaker-counter component that produces the intrinsic timing signal underlying the internal representation of a time interval to be judged, information-processing models of timing propose at least two other major stages of processing referred to as the memory and decision-making components, respectively (e.g., Church, 1984, 1989; Franssen & Vandierendonck, 2002; Treisman, 1963; Wearden, 1999). When performing a temporal reproduction task, the timing signal from the counter (i.e., the number of pulses counted during the target interval) is stored in a reference memory during timing of the reproduction interval. The internal representation of the target duration in reference memory can be retrieved by the decision-making component which compares the retrieved target duration with the current pulse count accumulated during the reproduction interval. Hence, it becomes obvious that, although not directly involved in the timing process in its narrow sense, both the memory and the decision-making components may have a major impact on the outcome of the entire timekeeping process. Therefore, it appears reasonable to consider the possibility that the effect of nontemporal stimulus size could arise from the memory or decision-making stages rather than from the pacemaker-counter stage of the psychological timing process.

A possible explanation for why the effect of nontemporal stimulus size became evident only when stimulus size was experimentally varied during the target interval, refers to the reference memory as the origin of the effect of nontemporal stimulus size on reproduced duration. Based on this notion, nontemporal stimulus size may affect the representation of the timing signal of the target duration in reference memory. From this perspective, the

representation of a timing signal from the pacemaker-counter component stored in reference memory may be systematically biased by nontemporal stimulus size, with larger stimulus size resulting in a longer internal representation of the target duration stored in reference memory. As a consequence, target durations indicated by larger nontemporal stimuli will lead to longer reproduced durations compared to the same target duration indicated by smaller nontemporal stimuli. When nontemporal stimulus size is experimentally varied during the reproduction rather than during the target interval, no such effect can be expected. The reason for this is twofold: First, nontemporal stimulus size during the target interval remains constant and, thus, the target duration stored in reference memory will not be biased by differences in stimulus size. Second, duration of the reproduced interval will not be encoded in reference memory before being compared to the representation of the target interval. Rather, temporal information about the ongoing duration will be retrieved from some other store, such as the pacemaker-counter component or working memory, and directly compared to the target duration stored in reference memory (Baudoin et al., 2006; Franssen & Vandierendonck, 2002; Karger et al., 2002; Mioni et al., 2014; Zakay & Block, 1997). Therefore, the effect of nontemporal stimulus size on reproduced duration cannot become effective when stimulus size is varied during the reproduction interval. Based on these considerations, the current data do not really fit with the idea that time and size are psychologically represented by a common metric as suggested by Walsh's (2003) notion of a generalized magnitude system.

This interpretation is supported by a most recent study on the effect of numerical magnitude on reproduced duration. In a series of experiments, Cai and Wang (2014) applied a temporal-reproduction paradigm almost identical to one used in the present study. They showed that large digits (8 and 9) are reproduced longer than small ones (1 and 2) when presented during the target interval. However, when the digits were presented during the reproduction interval, they failed to establish any effect of numerical stimulus magnitude on reproduced duration. An additional control experiment ruled out the possibility that this lack of a numerical magnitude effect was due to inattention to the digits presented during the reproduction interval. For this purpose, Cai and Wang (2014) also used a dual-task paradigm. Participants had to reproduce the target interval indicated by a green dot and, as a secondary task, had to identify the digit presented during the reproduction interval. Reproduced durations in this experiment did not differ from reproduced durations obtained in their other experiments where participants were not required to identify the digit presented during the reproduction interval. Based on their findings, Cai and Wang (2014) also

arrived at the conclusion that numerical stimulus magnitude appears to influence temporal representations in reference memory rather than the timing signal produced by the pacemaker-counter component.

In the present study, larger stimuli were reproduced temporally longer than smaller ones when stimulus size was experimentally varied during the target interval. This main effect of nontemporal stimulus size, however, was effectively modulated by target duration: While virtually no difference in reproduced duration could be observed for the 800-ms target interval, large stimuli were reproduced 3.1% and 6.1% longer than small stimuli for the 1000- and 1200-ms target intervals, respectively. A similar moderating effect of target duration was reported in previous studies (Cantor & Thomas, 1976; Long & Beaton, 1980; Rammsayer & Verner, 2014; Thomas & Cantor, 1976) where the effect of nontemporal stimulus size also was least pronounced for the shortest duration in a series of target durations. It is important to note that this finding held irrespective of whether the presented series of target durations was in the order of milliseconds or seconds. This, however, is a most important point because such a pattern of results indicates that this effect does not depend on a specific target duration (e.g., 1200 ms as in the present study) but on the relative duration of target interval within the range of the presented target durations.

It is also conceivable to locate the effect of nontemporal stimulus size on perceived duration at the stage of decision making. In a recent study, Yates et al. (2012) challenged the notion of a direct effect of nontemporal stimulus size on the timing signal per se as indicated by the number of pulses accumulated in the counter. When employing comparative judgments (i.e., the participant judged whether the first or the second of two stimuli was presented longer), Yates et al. (2012) found a positive effect of stimulus size on perceived duration. However, when using equality judgments (i.e., the participant judged whether two stimuli were presented for the same duration or for different durations), larger stimuli were judged as shorter in duration compared to smaller stimuli. This unexpected pattern of results suggests that nontemporal stimulus size may merely bias decisions about duration as a function of the judgment method rather than affecting the genuine timing process. In the present study, only the manipulation interval during which small and large nontemporal stimuli were presented was experimentally varied while the judgment method and participants' response options were held constant. Therefore, it is rather unlikely that the effect of nontemporal stimulus size on reproduced duration observed when stimulus size was varied during the target interval and the absence of such an effect when stimulus size was varied during the reproduction interval, represent a decisional bias.

Conclusions

Taken together, the present study revealed a differential effect of nontemporal stimulus size on reproduced duration. Larger visual stimuli led to longer reproduced durations only when stimulus size was experimentally varied during the target but not during the reproduction interval. This finding clearly argues against the notion that nontemporal visual stimulus size directly influences the genuine timing processes (i.e., the timing signal produced by the pacemaker-counter component of the internal clock). Furthermore, our findings ruled out a decisional bias as a potential cause of the observed effect of stimulus size on reproduced duration. Our data rather suggest the effect of visual stimulus size to originate from the memory stage of temporal information processing. At this stage, the timing signal from the pacemaker-counter component is encoded in reference memory in order to provide a durable internal representation of the target duration. It is probably this reference duration stored in memory that is effectively influenced by visual nontemporal stimulus size. This conclusion is consistent with the outcome of a study by Ono and Kawahara (2007). These authors altered apparent stimulus size of a visual object by means of the Ebbinghaus illusion while its physical size remained invariant. Most interestingly, the perceived duration for apparently larger stimuli was longer than that of apparently smaller stimuli presented for the same duration. This finding also is indicative of an effect of nontemporal visual stimulus size on perceived duration at a higher level or a later stage of information processing (Ono & Kawahara, 2007; Rammsayer & Verner, 2014). Future studies should be designed to directly and systematically examine the crucial role of reference memory for mediating the effect of nontemporal stimulus magnitude on perceived duration. To further elucidate the underlying mechanisms in reference memory, experimental manipulations could be utilized such as inducing an overload in temporal memory (cf. Grondin, 2005) or manipulating the delay separating the presentation of the target interval from the onset of the reproduction interval (cf. Gamache & Grondin, 2010). In addition, as memory bias and distortion of temporal memory were shown to be positively related to activation of the right precuneus (Harrington et al., 2004), also neuroimaging studies may provide a feasible, complementing approach to prosecute the underlying mechanisms.

Keywords: pacemaker-counter model, stimulus size, time perception, perceived duration, temporal reproduction, reference memory, magnitude system

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