Evidence for different processes involved in the effects of nontemporal stimulus size and numerical digit value on duration judgments

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Perceived duration has been shown to be positively related to task-irrelevant, nontemporal stimulus magnitude. To account for this finding, Walsh's (2003) *A Theory of Magnitude* (ATOM) model suggests that magnitude of time is not differentiated from magnitude of other nontemporal stimulus characteristics and collectively processed by a generalized magnitude system. In Experiment 1, we investigated the combined effects of stimulus size and numerical quantity, as two nontemporal stimulus dimensions covered by the ATOM model, on duration judgments. Participants were required to reproduce the duration of target intervals marked by Arabic digits varying in physical size and numerical value. While the effect of stimulus size was effectively moderated by target duration, the effect of numerical value appeared to require attentional resources directed to the numerical value in order to become effective. Experiment 2 was designed to further elucidate the mediating influence of attention on the effect of numerical value on duration judgments. An effect of numerical value was only observed when participants' attention was directed to digit value, but not when participants were required to pay special attention to digit parity. While the ATOM model implies a common metrics and generalized magnitude processing for time, size, and quantity, the present findings provided converging evidence for the notion of two qualitatively different mechanisms underlying the effects of nontemporal stimulus size and numerical value on duration judgments. Furthermore, our data challenge the implicit common assumption that the effect of numerical value on duration judgments represents a continuously increasing function of digit magnitude.

Introduction

A large number of studies reported that perceived duration and duration judgments are positively related to various aspects of nontemporal stimulus properties such as brightness, stimulus size, numerosity, stimulus complexity, or novelty (for a concise review, see Eagleman & Pariyadath, 2009). A prevalent and highly influential conceptual framework to account for a positive correlation between nontemporal stimulus magnitude and perceived duration originated from Walsh's (2003) idea of a generalized magnitude system. According to his *A Theory of Magnitude* (ATOM) model, magnitudes across different stimulus dimensions are collectively processed by a generalized magnitude system. More precisely, the ATOM model assumes common cortical metrics for the processing of various dimensions of magnitude information, such as time, space, size, and quantity, as the neural basis for the observed mutual interactions of time and nontemporal stimulus attributes. This generalized magnitude system can be automatically activated by input from the various magnitude dimensions inherent in a given stimulus and irrespective of whether this magnitude dimension is task-relevant or is not. Therefore, in a duration judgment task, for example, magnitude of time is not differentiated from (task-irrelevant) magnitude of nontemporal stimulus size and, as a result, large stimuli are judged to last longer than small stimuli presented for exactly the same time. Against this background, the major goal of the present study was to investigate the combined effects of stimulus size and numerical quantity, as two nontemporal stimulus dimensions covered by the ATOM model, on duration

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judgments. For this purpose, participants were required to reproduce the duration of target intervals marked by Arabic digits varying in both physical size and numerical value.

To the best of our knowledge, Mo and Michalski (1972) were the first to systematically study the effect of stimulus size on perceived duration. When presenting two circles, one smaller than the other, for the same duration of either 450 or 510 ms, their participants consistently judged the larger circle to be presented longer than the smaller one. In a series of subsequent experiments, Thomas and Cantor (1975, 1976) also found that large visual stimuli presented for the same duration as small stimuli appeared to have lasted longer. In their experiments, filled circles with diameters of 8.33 and 10.32 mm, for small and large stimuli, respectively, were presented for either 30 or 70 ms. These findings were confirmed by additional studies employing basically the same methodology but display times of either 20 and 50 ms (Cantor & Thomas, 1976) or 40 and 70 ms (Long & Beaton, 1980). More recently, this effect of nontemporal stimulus size on duration judgments was shown to also hold for longer durations ranging from 600 to 1800 ms (Rammsayer & Verner, 2014; Verner & Rammsayer, 2011; Xuan, Zhang, He, & Chen, 2007).

While the first systematic study on the effect of nontemporal stimulus size on duration judgment can be traced back to the year 1972, it was only in 2007 that similar studies on the effect of numerical digit value on duration judgments have been published. From then on, however, an increasing number of psychophysical studies provided evidence that duration judgments are also influenced by task-irrelevant numerical digit value. Typically, large numerical digit values (e.g., 8 or 9) were judged to last longer than small digit values (e.g., 1 or 2) when the digits were presented with the same stimulus duration. This pattern of results could be established for stimulus durations in the subsecond range (Cai & Wang, 2014; Chang, Tzeng, Hung, & Wu, 2011; Hayashi et al., 2013; Vicario et al., 2008; Xuan et al., 2007; Xuan, Che, He, & Zhang, 2009) as well as in the second range (Lu, Hodges, Zhang, & Zhang, 2009; Oliveri et al., 2008).

These effects of nontemporal stimulus magnitude on perceived time has been demonstrated with different psychophysical procedures. In numerous studies (e.g., Cantor & Thomas, 1976; Long & Beaton, 1980; Mo & Michalski, 1972; Thomas & Cantor, 1975, 1976) category ratings had been used to quantify the effect of nontemporal stimulus size on perceived duration. With this duration scaling procedure, the experimenter presents a temporal interval and the participant locates its perceived duration in one of *n* predefined categories, which are ordered by temporal magnitude. Also a relatively large number of studies applied a Stroop-like interference paradigm (e.g., Dormal, Seron, & Pesenti, 2006; Xuan et al., 2007) where error rate of temporal judgments served as an indirect measure of perceived duration. Other studies used scaling methods, such as the method of reproduction, for a direct assessment of perceived duration (e.g., Cai & Wang, 2014; Chang et al., 2011; Rammsayer & Verner 2014). The influence of nontemporal stimulus magnitude on perceived time could be confirmed with all these different psychophysical procedures (requiring different levels of working memory resources) and for different target intervals (ranging from tens of milliseconds to the suprasecond range). Taken together, these findings strongly suggest a rather robust effect of nontemporal stimulus magnitude on perceived time.

Although numerous studies have documented the effect of stimulus size and the effect of numerical digit value on duration judgments and perceived duration, next to nothing is known about the mutual interference on temporal information processing of both these nontemporal stimulus attributes combined. In this respect, also Walsh's (2003) idea of a generalized magnitude system is quite vague. Hence, what the ATOM model means for psychophysical or information-processing models of time perception remains a question still to be answered (Bueti & Walsh, 2009). Particularly, Walsh's theory appears rather underspecified with regard to the interaction of different nontemporal stimulus dimensions and their mutual effect on duration judgment and perceived duration (cf. van Opstal & Verguts, 2013). Nevertheless, a reasonable prediction, consistent with the notion of a generalized magnitude system, proceeds from the assumption of an additive effect of different nontemporal stimulus dimensions on time perception.

To be more specific, if the influences of nontemporal stimulus size and numerical digit value on duration judgments are both effective but independent of each other, we would expect a statistically significant main effect of stimulus size and numerical value, respectively, but no significant interaction between both these factors combined. With regard to both main effects, when applying the method of temporal reproduction, larger nontemporal magnitude of the target stimulus should result in longer reproduced durations than smaller nontemporal target stimulus magnitude. In other words, if target intervals are reproduced longer simply because they were marked by a larger physical stimulus or by a higher numerical digit value, longest reproduced durations should be expected for target intervals marked by large digits with high numerical value. Shortest reproduced durations, on the other hand, should be observed with target intervals marked by small digits with low numerical value, whereas reproduced durations of target intervals with either small digits with high numerical value or large digits with low numerical value should occupy an intermediary position.

Experiment 1

Based on these considerations, the aim of Experiment 1 was twofold. First, Experiment 1 was designed to provide first insights in the combined effects and the mutual interference of stimulus size and numerical digit value, as two nontemporal stimulus attributes, on temporal information processing. Second, the prediction of an additive effect of stimulus size and numerical digit value on duration judgment should be tested.

To obtain a most direct, sensitive, and reliable measure of the subjective experience of time as a function of experimentally varied nontemporal stimulus size and numerical digit value, the method of temporal reproduction was applied (cf. Doob, 1971; Rammsayer & Verner, 2014; Zakay, 1990). With this type of task, the participant is required to reproduce a previously presented target interval by means of some operation such as a key press (e.g., Mioni, Stablum, McClintock, & Grondin, 2014). In case of a positive effect of nontemporal stimulus size and/or numerical digit value on perceived duration, target stimuli marked by larger nontemporal stimulus magnitude should lead to longer reproduced durations than target stimuli with smaller nontemporal stimulus magnitude presented for the same duration.

Within the context of a timing task, nontemporal stimulus size and numerical digit value represent task-irrelevant stimulus attributes. To date, it is not known whether magnitude information of both these irrelevant stimulus attributes has to be processed consciously to effectively influence temporal processing (cf. Xuan et al., 2007; Yates, Loetscher, & Nicholls, 2012). Furthermore, it could be that the level of stimulus salience differs between the two irrelevant stimulus attributes. Therefore, to identify and control for a possible intervening effect of stimulus salience or attention, a dual-task paradigm was applied. In addition to temporal reproduction as the primary task, a secondary task was added where salience of the two nontemporal stimulus attributes was experimentally varied. In the size salience condition, participants were required to pay special attention and to explicitly process nontemporal stimulus size-related information, whereas in the numerical-value salience condition, participants' attention was directed to numerical digit value.

Method

Participants

The participants were three male and 27 female adult volunteers ranging in age from 19 to 43 years (mean age ± *SD*: 22.5 ± 4.8 years). All participants were undergraduate psychology students and received course credit for taking part in this experiment. 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 Optiplex 760 computer (Dell, Inc., Round Rock, TX) connected to a 17-in. monitor (Samsung SyncMaster 172N; Samsung Electronics GmbH, Schwalbach, Germany) 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). Visual stimuli indicating the target interval were Arabic digits of a low numerical value (2 or 3) or of a high numerical value (8 or 9). Low and high digits were presented in two different sizes subtending a visual angle of 1.2° (small stimulus size) and 8.0° (large stimulus size), respectively. Reproduction intervals were indicated by a fixation cross of a constant size subtending a visual angle of 2.0°. All stimuli were presented in black color on a white background.

Each participant performed two versions of the reproduction task conforming to the two stimulus-attribute relevance conditions with attention directed to either stimulus size or numerical value of the stimulus. Order of conditions 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. 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). Therefore, the longest target duration was chosen not to exceed this critical value.

An experimental block consisted of 16 presentations of each target interval resulting in a total of 48 trials. The 16 presentations of each target interval comprised four trials of each possible factorial combination of stimulus size (small and large) and numerical value (low and high). 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 the fixation cross. Participants were instructed to terminate the reproduction interval by pressing a designated response button when its duration was perceived as temporally identical to the corresponding target interval. After termination of the

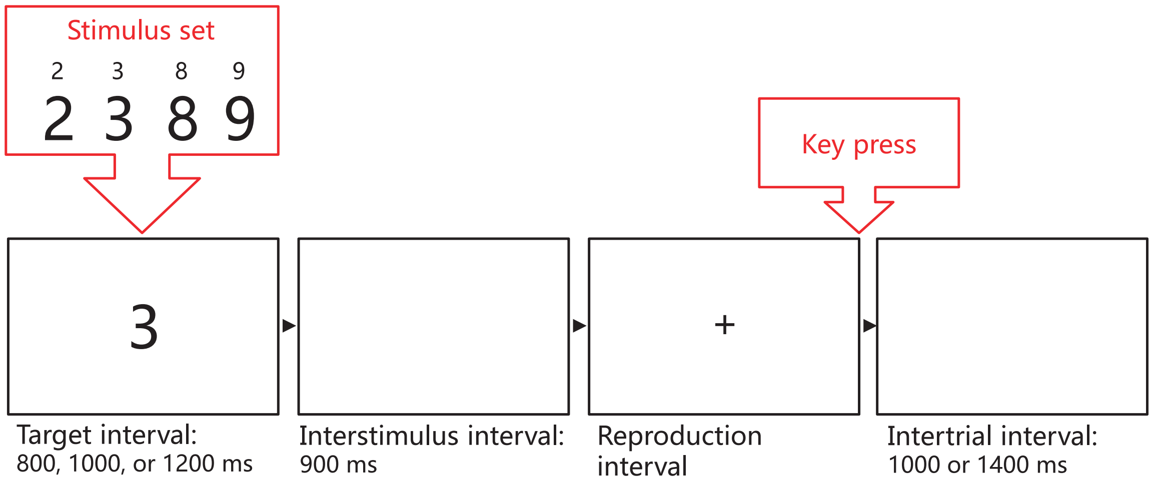

Figure 1. A sample trial of the experimental task. In the present example, the target interval consisted of the digit 3 presented for either 800, 1000, or 1200 ms. After a 900-ms interstimulus interval (blank screen), the reproduction interval marked by a fixation cross was started. The participant terminated the reproduction interval by pressing a response button when he/she perceived the reproduction interval as temporally identical to the immediately preceding target interval. In the stimulus relevance condition where attention was directed to stimulus size, participants had to press one of two designated response buttons if the physical digit size was small and the other one if the physical digit size was large. In the condition where attention was directed to the numerical value of the target stimulus, stimulus size was irrelevant and response buttons corresponded to the numerical value of the stimulus (i.e., low = digits 2 and 3, or high = digits 8 and 9). The next trial began after an intertrial interval of either 1000 or 1400 ms.

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. On each trial, the reproduced duration was logged with an accuracy of ±1 ms.

In addition to the temporal reproduction task, participants were required to indicate whether the nontemporal target stimulus was either small or large or whether it had a low (digits 2 and 3) or high (digits 8 and 9) numerical value. For this latter task, participants were instructed that there was a low value and a high value digit set consisting of the digits 2 and 3 and the digits 8 and 9, respectively. In the stimulus relevance condition where attention was directed to stimulus size, participants had to press one of two designated response buttons in order to terminate the reproduction interval if the size of the stimulus indicating the target interval was small and the other one if a large stimulus was displayed. In the condition where attention was directed to the numerical value of the target stimulus, stimulus size was irrelevant and response buttons corresponded to the numerical value (low or high) of the stimulus. The assignment of response button to hand was held constant within each participant but was balanced across participants. Each participant performed two blocks of the reproduction task where attention was directed to stimulus size and two blocks where attention was directed to the numerical digit value. Order of blocks was balanced across participants. A sample trial of the experimental task is given in Figure 1.

As a quantitative measure of perceived duration, mean reproduced durations (MRDs) were computed for each experimental condition. The effects of stimulus size and numerical value on reproduced duration were defined as the difference between the MRDs for the large and the small stimuli and between the MRDs for the high and the low numerical values, respectively.

Experimental design

Applying a within-subjects design, the present study investigated the effects of nontemporal stimulus size and numerical stimulus value on perceived duration of three different target durations as a function of stimulus attribute relevance. For statistical analysis, four-way within-subjects analysis of variance (ANOVA) was performed with the repeated-measures factors target duration (800, 1000, and 1200 ms), stimulus size (small and large), numerical value (low and high), and stimulus attribute relevance (attention directed to physical digit size and attention directed to numerical digit value). For all post hoc comparisons, Tukey's Honestly Significant Difference (HSD) tests (see Kirk, 1995) were computed. To protect against violations of sphericity, Greenhouse–Geisser corrected p values will be reported where appropriate (cf. Geisser & Greenhouse, 1958).

	Target interval			Across all target intervals
	800 ms	1000 ms	1200 ms	
Stimulus size				
Small	813	927	1036	925
Large	844	987	1094	975
Numerical value				
Low	832	955	1060	949
High	825	960	1070	952
Stimulus attribute relevance				
Stimulus size	825	963	1067	952
Numerical value	832	951	1063	949

Table 1. Mean reproduced durations for each target interval and across all target intervals as a function of stimulus size, numerical value, and stimulus attribute relevance. *Note*: All data in milliseconds.

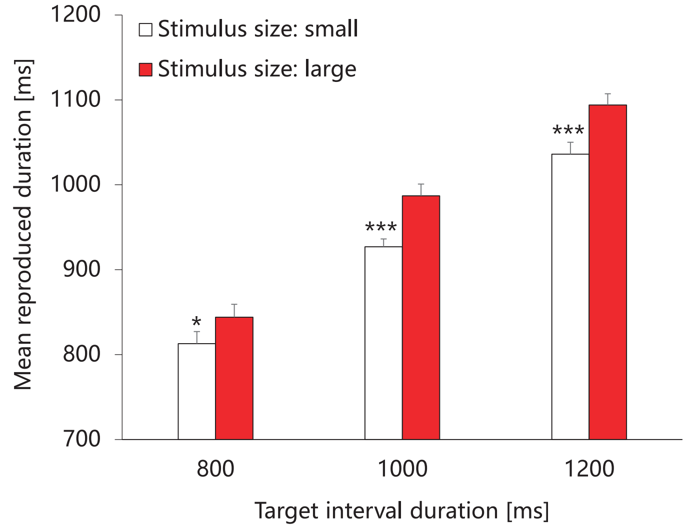

Figure 2. Mean reproduced durations for small and large physical stimulus size as a function of target duration. Error bars: 95% confidence interval (CI) calculated as recommended by Baguley (2012). *Significantly different from respective large physical stimulus size ($p < 0.05$). ***Significantly different from respective large physical stimulus size ($p < 0.001$).

Results

To control for outliers, we applied a standard trimming procedure similar to the one suggested by Chang et al. (2011). In a first step, for each participant, all reproduced durations that were more than ±2 *SD*s from that participant's mean reproduced duration for a given experimental condition were considered invalid trials and, therefore, not included in further data analysis. By applying this criterion, 4.4% of all trials were removed from data analysis. Next, each participant's remaining reproduced durations were submitted to a one-way ANOVA with target intervals (800, 1000, and 1200 ms) as three levels of a repeated-measures factor. The lack of a significant main effect as well as any nonsignificant differences among the three factor levels would provide an indication of an individual's inability to follow the instruction to reproduce the target intervals. None of our participants, however, had to be excluded on the basis of this criterion.

Analysis of error rates on the two versions of the stimulus-attribute relevance condition yielded faultless performance with error rates of 0.00. This outcome indicated that all participants conformed to the instructions and directed their attention to either stimulus size or numerical value depending on task requirements. Means of reproduced durations for each target interval and across all target intervals as a function of stimulus size, numerical value, and stimulus attribute relevance are given in Table 1.

Four-way ANOVA revealed statistically significant main effects of target duration, $F(2, 58) = 206.94$, $p < 0.001$, $\eta_p^2 = 0.877$, and stimulus size, $F(1, 29) = 42.47$, $p < 0.001$, $\eta_p^2 = 0.594$. The significant main effect of target duration indicated longer MRDs with increasing duration of the target intervals. Subsequent post hoc tests revealed that MRDs of all three target intervals differed significantly from each other ($p < 0.001$). Furthermore, MRDs differed significantly as a function of stimulus size. The significant main effect of stimulus size on MRD indicated that digits presented at a large image size were reproduced longer than digits presented at a small image size; MRDs (± *SD*) were 925 ± 143 ms and 975 ± 151 ms for the small and the large stimulus size, respectively. With respect to numerical digit value, there was no statistically significant main effect of numerical value, $F(1, 29) = 0.32$, $p = 0.58$, $\eta_p^2 = 0.011$; MRDs were 949 ± 145 ms and 952 ± 147 ms for digits of low and high numerical magnitude, respectively. Also no main effect of stimulus attribute relevance on MRD could be established, $F(1, 29) = 0.10$, $p = 0.75$, $\eta_p^2 = 0.004$; MRD was 952 ± 147 ms when participants' attention was directed to stimulus size and 949 ± 150 ms when participants' attention was directed to the numerical value of the digits presented during the target interval.

A statistically significant interaction between target duration and stimulus size, $F(2, 58) = 3.50$, $p < 0.05$, $\eta_p^2 = 0.108$, indicated that, although large stimuli were reproduced longer than small stimuli for all target durations, this effect was much stronger for the 1000- and 1200-ms target durations compared to the 800-ms target duration (see Figure 2).

Also the interaction between numerical value and stimulus attribute relevance became statistically significant, $F(1, 29) = 4.79$, $p < 0.05$, $\eta_p^2 = 0.142$. Although post hoc Tukey tests failed to show any significant differences, this interaction suggested that, when participants' attention was focused on numerical digit

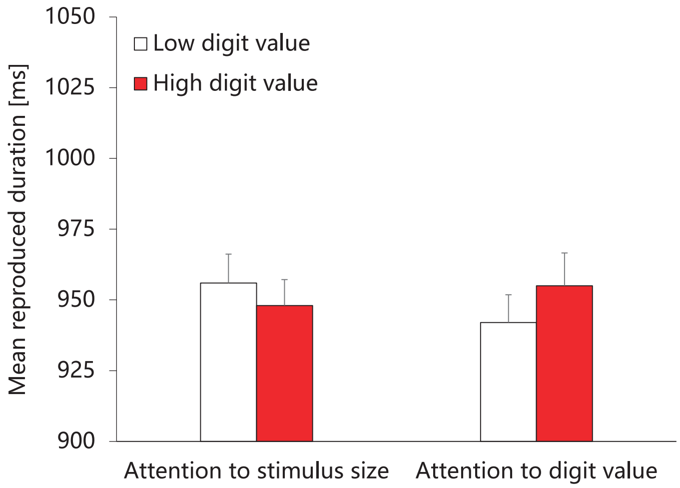

Figure 3. Mean reproduced durations for low and high numerical digit values when attention was paid to physical stimulus size and numerical digit value, respectively. Please note that, although the interaction between numerical value and stimulus attribute relevance was statistically significant, orthogonal contrasts did not reach the 5%-level of statistical significance. Error bars: 95% CI calculated as recommended by Baguley (2012).

value rather than on physical digit size, they tended to perceive digits of a large numerical magnitude to last longer than digits of smaller numerical magnitude presented for the same duration; MRDs were 942 ± 150 ms for low and 955 ± 152 ms for high numerical values, respectively. However, when participants were instructed to pay attention to physical digit size, MRDs tended to be longer for digits with low (956 ± 147 ms) than for digits with high (948 ± 149 ms) numerical value (see Figure 3). No other interactions reached the 5% level of statistical significance.

Discussion

The outcome of Experiment 1 is consistent with numerous previous studies in showing that perceived duration increases with increasing nontemporal stimulus size. While these earlier studies established the effect of stimulus size on perceived duration by using geometrical shapes, such as circles (e.g., Mo & Michalski, 1972; Rammsayer & Verner, 2014; Thomas & Cantor, 1975, 1976), squares (e.g., Rammsayer & Verner, 2014; Xuan et al., 2007), or nonsense forms (Cantor & Thomas, 1976), the present study provided first evidence that the effect of stimulus size on duration judgments also holds for images of digits.

This main effect of stimulus size on reproduced duration, however, was effectively modulated by target duration: While, with the 800-ms target duration, large stimuli were reproduced 3.8% longer than small stimuli, this difference increased to 6.5% and 5.6% for the 1000- and 1200-ms target duration, respectively. Such a moderating effect of target duration on the effect of stimulus size has been already reported in previous studies (Cantor & Thomas, 1976; Long & Beaton, 1980; Rammsayer & Verner, 2014, 2015; Thomas & Cantor, 1976) where the effect of nontemporal stimulus size also was least pronounced for the shortest duration in the series of target durations applied.

Unlike stimulus size, no indication of a main effect of numerical digit value was obtained in Experiment 1. This was a rather unexpected result given the substantial number of recent studies reporting longer perceived duration for high compared to low numerical digit values (e.g., Cai & Wang, 2014; Chang et al., 2011; Hayashi et al., 2013; Lu et al., 2009; Oliveri et al., 2008; Vicario et al., 2008; Xuan et al., 2007). Furthermore, our findings indicated that the effect of numerical digit value on reproduced duration seems to depend upon attention paid to this nontemporal stimulus dimension. As orthogonal contrasts assessed by post hoc Tukey's HSD tests did not reach the 5% level of statistical significance, the moderating influence of attentional processes on the effect of numerical digit value on duration judgments remained rather unclear.

Nevertheless, the observed overall pattern of results provided evidence against the notion of an additive effect of stimulus size and numerical digit value on reproduced duration as well as some indications for qualitatively different processes involved in the effects of stimulus size and numerical digit value on temporal information processing: First, a main effect on MRDs could be established for stimulus size, but not for numerical digit value. This outcome clearly argues against the notion of an additive effect of both nontemporal stimulus dimensions on reproduced durations. Furthermore, while the effect of stimulus size was effectively moderated by target duration, the effect of numerical digit value appeared to require attentional resources directed to the digit value in order to become effective. These differential findings were rather unexpected in the light of Walsh's (2003) theory of magnitude, which implies a common metrics and generalized magnitude processing for time, size, and quantity.

It should be noted that this line of argument proceeds from the implicit assumption that all dimensions of magnitude information are created equal. There are, however, other possible explanations. For example, most recently, Cai and Connell (2015) have shown that how strongly a dimension of stimulus magnitude is biased and biases other dimensions depends on acuity of its memory representation. Based on this finding, it seems conceivable that numerical digit value has a weaker effect than physical stimulus size in influencing the perception of time. Such a notion may also explain the finding that numerical digit value did not affect reproduced duration when attention was not explicitly paid to it. Eventually, another possible account of the observed differential effects of physical stimulus size and numerical digit value is that the encoding of stimulus size is automatic (regardless of whether or not it is task-relevant), while the encoding of numerical digit value is less so and, thus, requires more attention to be encoded.

Experiment 2

An additional experiment was designed to further elucidate the influence of numerical digit value on duration judgments with particular focus on the interaction between numerical value and stimulus attribute relevance. For that purpose, and to avoid unwanted additional experimental noise, only numerical digit value, but not physical digit size, was experimentally varied in Experiment 2.

A possible reason that may account for the inconclusive finding concerning the effect of numerical value on reproduced duration could be inappropriate experimental variation of digit values. In Experiment 1, the Arabic digits 2 and 3 and the Arabic digits 8 and 9 were used for indicating a low and high numerical digit value, respectively. We decided to refrain from including the digit 1 because of the markedly lower visual feature complexity of the digit 1 compared to the digits 2, 8, and 9. Such a difference in feature complexity may represent a crucial point as perceptual complexity of a stimulus has been reported to influence perceived duration (Cardaci, Gesù, Petrou, & Tabacchi, 2009; Folta-Schoofs, Wolf, Treue, & Schoofs, 2014; Palumbo, Ogden, Makin, & Bertamini, 2014).

At the same time, it should be pointed out that the majority of previous studies reporting an effect of numerical digit value on duration judgments especially employed the digit 1 (e.g., Cai & Wang, 2014; Lu et al., 2009; Vicario et al., 2008; Xuan et al., 2007, 2009). In this context, it is also important to note that, based on the outcome of their main experiment, Oliveri et al. (2008) hypothesized "that the reference to 1 may be the crucial element of the experimental design, its particular status leading to significant reduction in time estimation" (p. 310). Converging supporting evidence for this notion can be derived from data presented by Cai and Wang (2014, experiment 4a). Therefore, it cannot be ruled out completely that our decision not to include the digit 1 in Experiment 1 may have contributed to the absence of a significant main effect of numerical digit value on reproduced duration, although several studies demonstrated an effect of numerical digit value on perceived duration for low digit sets not including the digit 1 (e.g., Cappelletti, Freeman, & Cipolotti, 2009; Hayashi et al., 2013; Lu et al., 2009; Xuan et al., 2009). Against this background, we used the Arabic digits 1 and 2 as small-magnitude digits in the present experiment. As an additional measure to increase design sensitivity, we also increased the number of participants. Based on a power analysis using G*Power software (Faul, Erdfelder, Lang, & Buchner, 2007), a sample size of $N = 42$ participants will be sufficient to reliably identify a moderate effect for the interaction between numerical value and stimulus attribute relevance.

Method

Participants

A new group of eight male and 34 female undergraduate psychology students ranging in age from 18 to 29 years (mean age ± *SD*: 21.8 ± 2.5 years) participated in this experiment. They were naive about the purpose of this study, had normal or corrected-to-normal vision, and received course credit for taking part in this experiment. The study was approved by the local ethics committee and informed consent was obtained from each participant prior to the experiment.

Stimuli and procedure

Apparatus and stimuli were the same as in Experiment 1, with the exception that low numerical values were the digits 1 and 2. All digits were presented with a constant size subtending a visual angle of 2.6°.

The procedure was similar to that of Experiment 1. As in Experiment 1, participants were required to reproduce three different target intervals ranging from 800 to 1200 ms. There were 16 presentations of each target interval resulting in a total of 48 trials for each version of the task. The 16 presentations of each target interval consisted of four presentations of each possible numerical value (1, 2, 8, 9) presented in randomized order.

Again, each participant performed two versions of the reproduction task conforming to two stimulus-attribute relevance conditions. In one version, attention was directed to numerical parity and, in the other version, attention was directed to the numerical magnitude of the presented digits. Analogous to Experiment 1, in the stimulus relevance condition where attention was directed to numerical parity, participants had to press one of two designated response buttons in order to terminate the reproduc-

	Target interval			Across all target intervals
	800 ms	1000 ms	1200 ms	
Numerical value				
Low	841	1003	1111	985
High	858	1013	1134	1002
Stimulus attribute relevance				
Digital parity	854	1009	1114	992
Digital value	845	1007	1131	995

Table 2. Mean reproduced durations for each target interval and across all target intervals as a function of numerical digit value and stimulus attribute relevance. *Note*: All data in milliseconds.

tion interval if the presented digit was an even number (digits 2 and 8) and the other one if an odd number (digits 1 and 9) was displayed. In the condition where attention was directed to numerical magnitude, parity was irrelevant and participants were instructed that there was a low value and a high value digit set consisting of the digits 1 and 2 and the digits 8 and 9, respectively. With this latter task, response buttons corresponded to the low and high numerical value of the target stimulus. As in Experiment 1, response mapping was balanced across participants.

Results

To control for outliers, the same procedure as in Experiment 1 was used. By doing so, 3.6% of all trials were removed from data analysis because reproduced durations were more than ±2 *SDs* from the participant's mean reproduced duration for a given experimental condition. No participants, however, had to be excluded due to inability to follow the instructions to reproduce the target intervals and to direct their attention to either digit parity or numerical digit value. Mean reproduced durations for each target interval and across all target intervals as a function of numerical digit value and stimulus attribute relevance are given in Table 2.

For statistical analysis, a three-way within-subjects ANOVA was performed with the repeated-measurement factors target duration (800, 1000, and 1200 ms), numerical value (low and high), and stimulus attribute relevance (attention directed to digit parity and attention directed to numerical digit value). As in Experiment 1, for all post hoc comparisons, Tukey's HSD tests were computed and Greenhouse–Geisser corrected p values will be reported where appropriate.

Analysis of variance revealed statistically significant main effects of target duration, $F(2, 82) = 254.97$, $p < 0.001$, $\eta_p^2 = 0.861$, and numerical value, $F(1, 41) = 6.44$, $p < 0.05$, $\eta_p^2 = 0.136$. The significant main effect

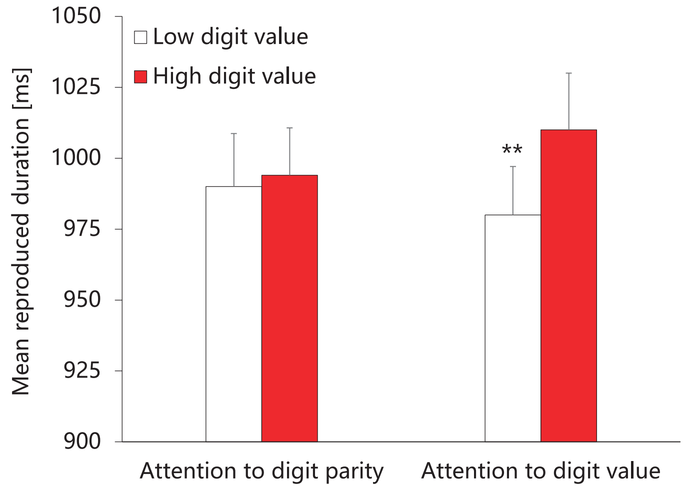

Figure 4. Mean reproduced durations for low and high numerical digit values when attention was paid to digit parity and digit value, respectively. Error bars: 95% CI calculated as recommended by Baguley (2012). **Significantly different from respective high digit value ($p < 0.01$).

of target duration was indicative of longer MRDs with increasing duration of the target interval. A post hoc Tukey's HSD test showed that MRDs of all three target durations differed significantly from each other ($p < 0.001$). The significant main effect of numerical value on MRD proved that high numerical digit values were reproduced longer than numerically low ones; MRDs were 1002 ± 152 ms and 985 ± 133 ms for numerically high and low digit values, respectively. No main effect of stimulus attribute relevance on MRD was found, $F(1, 41) = 0.01$, $p = 0.90$, $\eta_p^2 = 0.000$.

In addition, a statistically significant interaction between stimulus attribute relevance and numerical value could be established, $F(1, 41) = 5.43$, $p < 0.05$, $\eta_p^2 = 0.117$. Post hoc analysis revealed virtually identical MRDs for low (990 ± 148 ms) and high (994 ± 166 ms) numerical digit values when attention was directed to digit parity. When attention was directed to numerical digit value though, digits of high numerical value were reproduced significantly longer than digits of low numerical value ($p < 0.01$); MRDs were 980 ± 149 ms and 1010 ± 168 ms for low and high numerical digit values, respectively (see Figure 4). No other interactions reached the 5% level of statistical significance.

In a next step of data analysis, we investigated the effect of absolute numerical digit value on reproduced duration. For this purpose, we focused on the task condition where attention was directed toward numerical value, as the effect of numerical digit value was limited to this task condition. Figure 5 (right panel) shows mean MRDs across all target durations for each

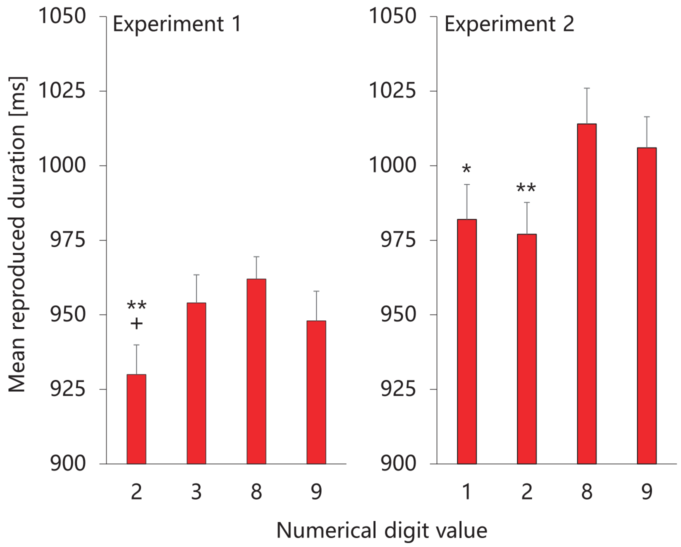

Figure 5. Mean reproduced duration as a function of numerical digit value when attention was paid to digit value in Experiment 1 (left panel) and Experiment 2 (right panel). Error bars: 95% CI calculated as recommended by Baguley (2012). *Significantly different from digit 8 ($p < 0.05$). **Significantly different from digit 8 ($p < 0.01$). +Significantly different from digit 3 ($p < 0.05$).

numerical digit value. Visual inspection of Figure 5 clearly indicates that MRDs cannot be considered a continuously increasing function of numerical digit value. An additional one-way ANOVA with numerical value (1, 2, 8, and 9) as four levels of a repeated-measurement factor yielded a statistically significant effect of digit value, $F(3, 123) = 5.10$, $p < 0.01$, $\eta_p^2 = 0.111$. Post hoc tests showed that the effect of numerical digit value on reproduced duration was caused by a significantly longer MRD for digit 8 (1014 ± 174 ms) compared to digit 1 (982 ± 156 ms; $p < 0.05$) and digit 2 (977 ± 148 ms; $p < 0.01$), whereas MRD of the largest digit 9 (1006 ± 168 ms) did not differ significantly from MRD of any of the other digits.

As this finding was rather unexpected, we reanalyzed the effect of each single numerical digit value on reproduced duration for Experiment 1 in exactly the same way. As for Experiment 2, a one-way ANOVA with numerical digit value (2, 3, 8, and 9) as a repeated-measure factor revealed a significant effect of digit value, $F(3, 87) = 4.67$, $p < 0.01$, $\eta_p^2 = 0.139$. Post hoc Tukey tests showed that the smallest digit 2 (930 ± 148 ms) was reproduced significantly shorter than the digit 3 (954 ± 156 ms; $p < 0.05$) and the digit 8 (962 ± 150 ms; $p < 0.01$), respectively. Again, the reproduced duration of the largest digit 9 (948 ± 157 ms) was not significantly different from any of the other digits (see Figure 5, left panel).

Discussion

In order to enhance the sensitivity of our experimental design with regard to the effect of numerical digit value on reproduced duration, several measures were taken in Experiment 2. In contrast to Experiment 1, we (a) reduced experimental noise by discarding stimulus size as an additional experimental variable, (b) increased the sample size from 30 to 42 participants, and (c) replaced the digit 3 by the digit 1 as the second small numerical digit value in addition to the digit 2. Apparently, our measures taken to increase design sensitivity to further elucidate possible effects of numerical digit value on reproduced duration proved to be effective. When participants reproduced the duration of Arabic digits, the set of digits with high numerical value were reproduced longer than the set with low numerical digit value presented for the same duration. Most interestingly, however, as in Experiment 1, this effect of numerical digit value was effectively moderated by stimulus attribute relevance. To be more specific, an effect of numerical digit value was only observed when participants' attention was directed to digit value, but not when participants were required to pay special attention to digit parity.

While our first two measures certainly increased task sensitivity and statistical power, it remained unclear to what extent replacing the digit 3 by the digit 1 had an effect on the outcome of Experiment 2. The vast majority of studies on the effect of numerical digit value on perceived duration and duration judgments included the digit 1 in the set of digits representing the small numerical digit magnitude (e.g., Cai & Wang, 2014; Cappelletti et al., 2009, 2011; Chang et al., 2011; Lu et al., 2009; Oliveri et al., 2008; Vicario et al., 2008; Xuan et al., 2007, 2009). Unfortunately, however, none of these studies did report the effect of numerical digit value on perceived duration separately for each single digit but rather presented mean results for the small- and large-magnitude digit sets. The more detailed analysis of our data, however, showed that the effect of numerical digit value, originally observed for the small- (digits 1 and 2) and large-magnitude (digits 8 and 9) digit sets, was caused by significantly longer reproduced durations in response to digit 8 compared to digits 1 and 2. At the same time, there was no indication for a linear increase in reproduced duration as a function of numerical digit value. A reanalysis of the data from Experiment 1 basically corroborated this result. This rather unexpected finding is not consistent with the common implicit notion that the effect of numerical digit value on duration judgments depends on the mere number categories of low and high values.

General discussion

The major goal of the present study was to investigate the combined effects of stimulus size and numerical digit value, as two nontemporal stimulus dimensions known to influence duration judgments, on reproduced duration. A popular and highly influential conceptual framework to account for a functional relationship between nontemporal stimulus magnitude and perceived duration originated from Walsh's (2003) idea of a generalized magnitude system. According to this theoretical account, magnitudes across different stimulus dimensions, such as stimulus size and numerical quantity, are collectively processed by a generalized magnitude system controlled by the parietal cortex (see also Bueti & Walsh, 2009; Conson, Cinque, Barbarulo, & Trojano, 2008; Srinivasan & Carey, 2010). However, what Walsh's (2003) generalized magnitude account means for psychophysical or information-processing models of time perception remains a question still to be answered (Bueti & Walsh, 2009). Particularly, Walsh's theory appears rather underspecified with regard to the nature of the interaction of different stimulus dimensions and their combined effects on perceived duration and duration judgments.

Overall, the outcome of Experiments 1 and 2 provided converging evidence against the assumption of a unitary, common magnitude system underlying the effects of stimulus size and numerical value on perceived duration. According to Walsh's (2003) notion of a common generalized magnitude system, an additive effect of stimulus size and numerical digit value on reproduced durations should have been the most likely outcome. In Experiment 1, digits presented at a large image size were reproduced longer than digits presented at a small image size. There was, however, no indication of a main effect of numerical digit value or of a combined effect of numerical digit value and physical digit size on reproduced durations. Rather, participants tended to perceive digits of a large numerical magnitude to last longer than digits of smaller numerical magnitude only when their attention was focused on numerical digit value rather than on physical digit size. Thus, the pattern of results obtained in Experiment 1 suggested a differential influence of nontemporal stimulus size on reproduced duration in comparison with numerical digit value and clearly argued against an additive effect of both nontemporal stimulus dimension combined.

Furthermore, the lack of an interactive effect of stimulus size and stimulus attribute relevance indicated that the influence of stimulus size on perceived duration does not depend on the amount of attention paid to this nontemporal stimulus dimension. This latter finding is consistent with previous studies (Rammsayer & Verner, 2014, 2015) as well as with the notion that attention does not affect perceived appearance of a target stimulus (Blaser, Sperling, & Lu, 1999; Schneider, 2006; Schneider & Komlos, 2008). It also supports Xuan et al.'s (2007) assumption that stimulus magnitude has not to be processed intentionally to effectively modulate perceived duration. Thus, magnitude information in the form of stimulus size appears to be processed automatically and beyond attentional control but still effectively influences perceived duration.

Unlike stimulus size, for the effect of numerical digit value on reproduced duration to become effective, participants' attention had to be directed toward the numerical value. This was shown in Experiment 1 where participants appeared to perceive digits of a large numerical magnitude to last longer than digits of smaller numerical magnitude only when their attention was directed toward the numerical digit value. In Experiment 2, this tendency could be statistically confirmed. Therefore, it seems that nontemporal stimulus magnitude in form of numerical value has to be processed consciously and intentionally to effectively influence perceived duration. This moderating effect of stimulus attribute relevance or attention observed with numerical digit value and the complete absence of such an attention-related moderating effect with regard to physical stimulus size may be indicative of two qualitatively different mechanisms underlying the influence of both these nontemporal stimulus dimensions on perceived duration. While the influence of nontemporal stimulus size on temporal information processing appears to be mediated automatically and beyond attentional control, the effect of numerical digit value seems to depend on attentional resources devoted to the processing of numerical digit information. This latter conclusion is consistent with the finding that the time–number association is effectively modulated by the availability of attentional resources in working memory processing (cf. Bi, Liu, Yuan, & Huang, 2014; Oliveri et al., 2008).

The notion of two qualitatively different mechanisms involved in the effect of nontemporal stimulus size and numerical digit value on temporal information processing is, at least indirectly, supported by reports suggesting partially independent (Cappelletti et al., 2009, 2011) or even two different (Agrillo, Ranpura, & Butterworth, 2010) processing systems for number and time. To the best of our knowledge, similar findings for stimulus size and time do not seem to exist. Additional converging evidence for the notion of distinct mechanisms underlying the influence of nontemporal stimulus size and numerical digit value on duration judgments comes from behavioral and neurophysiological studies challenging the existence of a shared magnitude representation for numerical value and physical size (e.g., Cantlon, Platt, & Brannon, 2008; Cohen Kadosh et al., 2007; Cohen Kadosh, Lammertyn, & Izard, 2008; Santens & Verguts, 2011).

While the effect of numerical value on reproduced duration was effectively moderated by attention paid to digit value, the influence of stimulus size on reproduced duration was found to vary as a function of target duration in the present study. This interaction between nontemporal stimulus size and duration of the target interval has been suggested to be indicative of a range or context effect (Rammsayer & Verner, 2014). Although the mechanisms and neural underpinnings underlying context effects on interval timing are still not well understood yet (Jazayeri & Shadlen, 2010; Ryan, 2011), as a most recent and empirically confirmed theoretical account, the internal reference model (Bausenhart, Dyjas, & Ulrich, 2014; Dyjas, Bausenhart, & Ulrich, 2012) emphasizes the crucial role of updating processes in reference memory as the major source of temporal context effects. Thus, within the framework of the internal reference model, the moderating influence of target duration on the effect of nontemporal stimulus size may point to reference memory as the origin of the effect of nontemporal stimulus size on perceived duration.

In a most recent study, Rammsayer and Verner (2015) showed that an effect of nontemporal stimulus size on reproduced duration occurred when stimulus size was varied during the target interval, but was absent when stimulus size was varied during the reproduced interval. This finding clearly argues against the notion that nontemporal stimulus size directly influences the timing processes at the sensory-perceptual level. Rather, the effect of stimulus size seems to originate from the memory stage of temporal information processing at which the timing signal from the internal clock mechanism is encoded in reference memory. Based on these considerations, the present findings are consistent with the notion that the effects of both nontemporal stimulus dimensions cannot be considered sensory-perceptual phenomena but seem to arise at a higher level of information processing. While the effect of numerical digit value on perceived duration depends on attentional mechanisms and working memory processing (Bi et al., 2014; Oliveri et al., 2008), the effect of nontemporal stimulus size appears to be mediated at the stage of reference memory (Rammsayer & Verner, 2015).

Previous studies (e.g., Cai & Wang, 2014; Cappelletti et al., 2009, 2011; Chang et al., 2011; Lu et al., 2009; Oliveri et al., 2008; Vicario et al., 2008; Xuan et al., 2007, 2009) reported that numerical digit value effectively influences the perception of time with higher numerical digit values resulting in longer perceived durations. These findings implied a linearly increasing relation between numerical digit value and perceived duration. A more closely examination of these findings, however, showed that low (for the most part the digits 1 and 2) and high (for the most part the digits 8 and 9) digit values were merged to small- and large-magnitude digits sets, respectively. Thus, statistical analyses were based on these digits sets rather than on single digit values and no information was provided with regard to specific digit values. Only in the studies by Cai and Wang (2014; figure 5) and Lu et al. (2009; figure 1) reproduced durations as a function of single numerical digit values were given. Visual inspection of these graphically presented data suggests that statistically significant increases in reproduced duration are unlikely to represent a linearly increasing function of numerical digit value. This conclusion was confirmed by the outcome of the present study. In Experiment 1, where digit size and numerical digit value were systematically varied, as well as in Experiment 2, where only numerical digit value was changed, the digit 2 was significantly underreproduced compared to digit 8. At the same time, in both experiments, the reproduced duration of digits 2 and 8 did not differ significantly from the reproduced duration of digit 9. This pattern of results suggests that the observed effect of numerical digit value on perceived duration may involve hitherto overlooked features of specific digits rather than or in addition to numerical value. Hence, the available data challenge the common implicit assumption that the effect of numerical digit value on duration judgment depends on the relative digit value and reflects a positive linear relationship between numerical magnitude and perceived duration. Further research is certainly needed to explore the decisive factors underlying the association between numerical digit value and perceived duration.

Taken together, the present study provided first evidence that stimulus size and numerical value, as two nontemporal stimulus dimensions shown to affect perceived duration, do not exert an additive effect on duration judgments. For an effect of numerical value on reproduced duration to occur, attention paid to digit value could be established as an essential prerequisite. On the other hand, the influence of stimulus size on reproduced duration did not rely upon the amount of attentional resources devoted to this nontemporal stimulus dimension. In addition, and maybe even more importantly, the effect of numerical value on duration judgment was not found to represent a continuously increasing function of numerical digit magnitude. This overall pattern of results is consistent with the notion that the effects of stimulus size and numerical value on temporal information processing involve qualitatively different mechanisms and are unlikely to be accounted for by a common generalized magnitude processing system underlying the representation of time, size, and numbers.

Keywords: time perception, perceived duration, stimulus size, numerical value, attention, A Theory of Magnitude (ATOM) model

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