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The effects of type of interval, sensory modality, base duration, and psychophysical task on the discrimination of brief time intervals

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Abstract The present study was designed to investigate the influences of type of psychophysical task (two-alternative forced-choice [2AFC] and reminder tasks), type of interval (filled vs. empty), sensory modality (auditory vs. visual), and base duration (ranging from 100 through 1,000 ms) on performance on duration discrimination. All of these factors were systematically varied in an experiment comprising 192 participants. This approach allowed for obtaining information not only on the general (main) effect of each factor alone, but also on the functional interplay and mutual interactions of some or all of these factors combined. Temporal sensitivity was markedly higher for auditory than for visual intervals, as well as for the reminder relative to the 2AFC task. With regard to base duration, discrimination performance deteriorated with decreasing base durations for intervals below 400 ms, whereas longer intervals were not affected. No indication emerged that overall performance on duration discrimination was influenced by the type of interval, and only two significant interactions were apparent: Base Duration × Type of Interval and Base Duration × Sensory Modality. With filled intervals, the deteriorating effect of base duration was limited to very brief base durations, not exceeding 100 ms, whereas with empty intervals, temporal discriminability was also affected for the 200-ms base duration. Similarly, the performance decrement observed with visual relative to auditory intervals increased with decreasing base durations. These findings suggest that type of task, sensory modality, and base duration represent largely independent sources of variance for performance on duration discrimination that can be accounted for by distinct nontemporal mechanisms.

Keywords Temporal processing · Filled and empty intervals · Sensory modality · Psychophysical task

Psychophysical research on human performance on duration discrimination provides, at least to some extent, a puzzling picture of rather inconsistent results. In his comprehensive review on psychological time, Grondin (2001) suggested various structural aspects that effectively modulate estimates of timing performance as a possible cause for these ambiguous findings. The term "structural aspects" refers to the physical characteristics of an interval (see Grondin, 2001) and, thus, not only comprises the type of interval (filled vs. empty) but also aspects such as the sensory modality of the signals that mark the intervals to be compared (e.g., auditory vs. visual) and the base duration of the intervals. In this context, base duration denotes the (range of) standard durations used in a given timing study. In studies on duration discrimination, commonly employed base durations are on the order of tens to hundreds of milliseconds (see Grondin, 2010; Penney, 2003). An additional source of variance that may also account for conflicting findings in studies on duration discrimination represents the psychophysical task applied for investigating discrimination performance (see Lapid, Ulrich, & Rammsayer, 2008; Ulrich, 2010).

One major reason for the difficulties to arrive at unambiguous conclusions or, at least, to explain some of the apparently existing contradicting findings in psychophysical research on duration discrimination, represents the fact that structural aspects of the intervals to be compared differ greatly across studies, and even between experiments within a given study. In order to arrive at any definitive statement, the influence of these major structural aspects, as well as the potential influence of the psychophysical task applied, has to be taken into account. On the basis of these considerations, the present article represents a mainly empirical contribution with the

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objective of a concurrent, systematic assessment of the effects of the above-mentioned major structural aspects and of the psychophysical task on the discrimination of brief time intervals.

In psychophysical studies on duration discrimination, basically two types of intervals are used (see Woodrow, 1951). One type is the *filled* interval and the other type is the *empty* interval. In filled intervals, a signal is presented continuously throughout the interval, whereas in empty intervals only the onset and the offset of the interval are marked by a brief sensory event. Thus, an empty interval is a silent duration with no signal present during the interval itself. In the literature, a highly puzzling picture of rather inconsistent findings arose with regard to the question of how type of interval affects performance on duration discrimination. Although some studies found better performance on duration discrimination with filled than with empty intervals (e.g., Abel, 1972a, 1972b; Rammsayer & Lima, 1991), other studies reported the opposite effect (e.g., Fraisse, 1978; Grondin, Meilleur-Wells, Ouellette, & Macar, 1998; Pfeuty, Ragot, & Pouthas, 2008). For example, Pfeuty et al. reported significantly better discrimination performance with empty than with filled intervals for a 600-ms base duration. This higher temporal accuracy of empty as compared to filled intervals is consistent with previous findings obtained with base durations ranging from 250 to 800 ms (e.g., Grondin, 1993; Grondin et al., 1998). It should be noted, however, that Pfeuty et al. proceeded from the questionable notion that the duration of an empty interval is represented by the time from onset of the first marker until onset of the second marker, whereas the other studies defined the duration of an empty interval as the silent duration *between* the two markers (i.e., from the offset of the first until the onset of the second marker). For a direct comparison of performance on duration discrimination with filled and empty intervals, studies should be considered only if the duration of the filled interval corresponds exactly to the time between the offset of the first marker and the onset of the second marker (for a comprehensive discussion of this fundamental problem see Rammsayer, 2010). Due to these highly ambiguous results, in his comprehensive reviews of the influence of filled and empty intervals on performance on duration discrimination in humans, Grondin (2001, 2003) arrived at the conclusion that, to date, no definitive statement on this issue can be made (see also Penney, 2003).

In a series of two experiments, designed to systematically investigate the influence of *base duration* on duration discrimination of filled and empty auditory intervals, Rammsayer (2010) used an adaptive psychophysical procedure based on a two-alternative forced-choice (2AFC) task. In his first experiment, he found significantly better performance on duration discrimination with filled than with empty auditory intervals for a 50-ms base duration, whereas virtually no difference between filled and empty intervals could be observed for a 1,000-ms base duration. Therefore, yet another experiment was performed to identify the critical base duration in which differences in the discrimination of filled and empty intervals begin to become apparent. For this purpose, seven levels of base duration were employed ranging from 50 to 1,000 ms. Again, findings indicated better performance on duration discrimination with filled relative to empty intervals at a base duration of 50 ms. No difference in discriminability of filled and empty intervals could be shown for longer base durations ranging from 100 to 1,000 ms.

The finding that, for a 50-ms base duration, temporal sensitivity was better with filled than with empty auditory intervals is consistent with the outcome of several previous studies employing an adaptive psychophysical procedure (e.g., Rammsayer, 1994a, 1994b; Rammsayer & Altenmüller, 2006; Rammsayer & Brandler, 2004; Rammsayer & Lima, 1991; Rammsayer & Skrandies, 1998). The absence of a filled–empty difference for longer auditory intervals, on the other hand, has been also reported by Fitzgibbons and Gordon-Salant (1994), using a base duration of 250 ms and an adaptive forced-choice task. It should be noted, however, that further studies, that employed other psychophysical tasks, yielded contradictory results. For example, Grondin (1993) observed better performance with empty, as opposed to filled, auditory intervals at a base duration of 250 ms when applying the method of single stimuli (Exps. 1 and 3) or a forced-choice task with two different intervals set at 241 and 259 ms (Exp. 3). Also using a non-adaptive procedure, Abel (1972a, 1972b) found superior discrimination performance with filled as compared to empty auditory intervals for base durations up to 640 ms. A cautionary note, however, is that Abel's data were based on two participants only and their previous experience with temporal discrimination tasks was not controlled for. These methodological weaknesses considerably limit the conclusions that can be drawn from her data. To what extent these inconsistent findings can be accounted for by the different psychophysical tasks applied, still is an open question. Furthermore, it remains to be seen whether Rammsayer's (2010) findings on filled and empty auditory intervals would also apply to visually presented intervals.

The difference limen (DL) is a fundamental concept in psychophysics (Gescheider, 1997; Guilford, 1954). It quantifies the minimal necessary physical difference in stimulus magnitude between two otherwise identical stimuli that allows a reliable discrimination of the two stimuli. Two of the most commonly used tasks in psychophysics for estimating DL are the reminder task and 2AFC task (e.g., Macmillan & Creelman, 2005). Therefore, the present article will focus on these types of tasks. Both these tasks are variants of the method of constant stimuli (Gescheider, 1997; Macmillan & Creelman, 2005). On each trial of the reminder task, the standard interval is presented prior to the comparison and, in addition, the comparison can be shorter or longer than standard. At the end of each trial, the participant indicates which of the two intervals was longer. The 2AFC task differs from the reminder task in at least one crucial feature. That is, in contrast to the reminder task, the presentation order of the standard and the comparison interval is randomly determined on each trial with both presentation orders <standard – comparison> and <comparison – standard> occurring with equal probability.

Although it is usually assumed that the two tasks yield identical DLs (e.g., Thompson, Schiffman, & Bobko, 1976; Wright, Buonomano, Mahncke, & Merzenich, 1997), this implicit assumption is not supported by experimental data (see Ulrich, 2010; Ulrich & Vorberg, 2009). In a first attempt to empirically study this issue in a more systematic way, Lapid et al. (2008) obtained DLs for the 2AFC task almost twice as large than those for the reminder task with filled intervals. In a subsequent study, Grondin and McAuley (2009) confirmed that this phenomenon also applies to empty intervals. Such discrepancies in DL estimates may account for some of the inconsistent findings when comparing performance on duration discrimination with filled and empty intervals across different experiments and/or studies. Because of the established impact of the psychophysical procedure on measured discrimination performance, type of psychophysical task should be experimentally controlled for and held constant when investigating the influence of other factors such as base duration, type of interval, or sensory modality on duration discrimination. Along these lines, Rammsayer and Ulrich (2012) examined whether this difference in DL estimates observed with the reminder and 2AFC tasks is influenced by the base duration of the standard stimulus. Using filled intervals ranging from 50 to 1,400 ms, they found no indication that the DL difference between the two tasks varied as a function of base duration. Unfortunately, a comparable systematic study on a possible mutual interaction of type of psychophysical task and base duration on temporal discrimination does not exist for empty intervals yet.

An ubiquitous finding in time psychophysics is that temporal acuity is much better for stimuli presented in the auditory than in the visual modality (Penney & Tourret, 2005; van Wassenhove, 2009). Thus, using auditory signals results in better performance on duration discrimination than using visual ones (e.g., Grondin, 2003; Rammsayer, Buttkus, & Altenmüller, 2012; Ulrich, Nitschke, & Rammsayer, 2006). By directly comparing filled and empty intervals, several studies showed that this superiority of the auditory over the visual domain applies to both types of intervals (e.g., Grondin et al., 1998; Stauffer, Haldemann, Troche, & Rammsayer, 2012). Nevertheless, some evidence suggests that auditory–visual differences may depend upon the range of base durations and the type of the psychophysical task (see Grondin, 2003).

At this point, it seems that performance on duration discrimination may depend on various structural factors of the intervals to be compared, such as type of interval, sensory modality, or base duration, as well as on the psychophysical task applied (see Allan, 1979; Fraisse, 1978; Grondin, 2001, 2003, 2008, 2010). Thus, all these potentially crucial factors should be controlled for or held constant when comparing performance on duration discrimination across different studies. Furthermore, studies would be highly desirable in which these factors are systematically varied within a given experiment. This latter approach not only could provide information on the general effect of each of these factors on performance on duration discrimination, but also would enable us to obtain additional information on the functional interplay and mutual interactions of some or all of these factors combined.

Up to date, to the best of our knowledge, no experimental study appears to exist that concurrently investigated the combined effects of these factors on duration discrimination performance in an orderly fashion. Therefore, the present study was designed to systematically assess differences in performance on duration discrimination as a function of *type of interval* (filled vs. empty), *sensory modality* (auditory vs. visual), *base duration* (standard intervals ranging from 100 to 1,000 ms), and *type of task* (reminder task vs. 2AFC task) within one large-scale psychophysical experiment. For this purpose, a mixed between-within-subjects design (Tabachnik & Fidell, 2001) was employed to largely avoid potential practice effects, as well as transfer effects from one experimental condition to the other due to perceptual learning (Karmarkar & Buonomano, 2003; Lapid, Ulrich, & Rammsayer, 2009; Nagarajan, Blake, Wright, Byl, & Merzenich, 1998; Wright et al., 1997). With regard to psychophysical tasks, there are two standard procedures for data collection—the adaptive and the nonadaptive procedure. With a typical nonadaptive procedure, several levels of the comparison stimulus are predetermined around the threshold region and administered to the participant several times in random order. With an adaptive procedure, on the other hand, levels of the comparison stimulus are not predetermined but are governed by the participant's response history. Lapid et al. (2008) showed that these two procedures yield virtually identical and equally stable DL estimates as an indicator of performance on duration discrimination. Thus, differences in DL estimates obtained with the reminder and 2AFC task do not seem to be affected by the psychophysical procedure applied. Over the past years, adaptive procedures enjoyed increasingly widespread use in psychophysical research because they avoid trials with an inefficient placement of comparison values (see Leek, 2001; Levitt, 1971). Therefore, adaptive versions of the reminder and 2AFC tasks were employed in the present study. With regard to base duration, an upper limit of 1,000 ms was chosen because it is known that, for interval durations exceeding 1,180 ms, explicit counting becomes a useful auxiliary timing strategy (Grondin, Meilleur-Wells, & Lachance, 1999).

Method

Participants

The participants were 63 male and 129 female adult volunteers (mean age 22.9 ± 4.12 years). All participants were undergraduate psychology students and received course credit for taking part in this experiment. They were randomly assigned to one of the eight experimental conditions. All participants were naïve as to the purpose of this study and had normal hearing and normal or corrected-to-normal vision. The study was approved by the local ethics committee.

Experimental design

The present study investigated the effects of Type of Interval (filled and empty), Sensory Modality (auditory and visual), and Type of Task (reminder task and 2AFC task) as between-subjects factors on duration discrimination as a function of Base Duration as a within-subjects factor. Six levels of base duration were created (100-, 200-, 400-, 600-, 800-, and 1,000-ms standard intervals). Trials of a given base duration were presented blockwise. That is, the duration of the standard interval was kept constant across the trials within a single block. Thus, the within-subjects factor Base Duration comprised six experimental blocks. Order of blocks was counterbalanced across participants. For statistical analysis, four-way mixed between- and within-subjects analysis of variance (Tabachnik & Fidell, 2001) with between-subjects factors Type of Interval, Sensory Modality, and Type of Task, and Base Duration as a within-subjects factor was performed. For all post-hoc comparisons, Tukey's HSD tests (see Kirk, 1995) were applied. To protect against violations of sphericity, Greenhouse–Geisser corrected p values will be reported, where appropriate (see Geisser & Greenhouse, 1958).

Apparatus and stimuli

The presentation of the intervals to be compared and the recording of participants' responses were controlled by a computer. Auditory filled intervals consisted of white noise from a computer-controlled sound generator (Phylab Model 1), presented binaurally through headphones (Vivanco SR85). Auditory empty intervals were marked by onset and offset white-noise bursts 3 ms in duration. Filled and empty intervals were presented with an intensity of 66 and 88 dB(A), respectively. These different levels of intensity were chosen to achieve equal loudness in the two conditions on the basis of the results of a prior pilot experiment. Visual stimuli were generated by a red LED (subtending a visual angle of 0.48°, viewing distance 60 cm, luminance 48 cd/m^2) positioned at eye level of the participant. The intensity of the LED was clearly above threshold, but not dazzling. Analogous to the auditory intervals, the visual filled intervals consisted of a red-light signal, whereas visual empty intervals were marked by 3-ms light flashes.

Procedure

Each block consisted of 64 trials, and each trial consisted of one standard interval and one comparison interval. The duration of the comparison interval varied according to an adaptive rule (Kaernbach, 1991) to estimate $c_{.25}$ and $c_{.75}$ of the individual psychometric function—that is, the two comparison intervals at which the response "longer" was given with a probability of .25 and .75, respectively. In each experimental block, two series of 32 trials were presented, one converging to $c_{.75}$ and one converging to $c_{.25}$. Trials from both series were randomly interleaved within a block. To estimate $c_{.75}$, the duration of the comparison interval was increased by Δ_+ ms if the participant had judged the comparison interval to be shorter, and decreased by Δ_- after a "long" judgment. The opposite step sizes were employed for $c_{.25}$. To increase the efficiency of the adaptive procedure, a larger step size was applied for the initial Trials 1–6 than for Trials 7–32 (see Levitt, 1971). Because the absolute precision of timing depends on the standard duration, the step sizes Δ_+ and Δ_- were adjusted for each base duration. For each base duration, step sizes as well as the initial value of the comparison interval were chosen on the basis of the results of a pilot experiment, and these are given in Table 1.

With the reminder task, the comparison interval always followed the standard interval, whereas with the 2AFC task, the order of presentation for the standard interval and the

Table 1 Initial values of the comparison intervals for the $x_{.25}$ and $x_{.75}$ series and step sizes Δ_+ and Δ_- for the $x_{.75}$ series as a function of standard duration

Base Duration	Initial Value of Comparison		Step Size Δ_-		Step Size Δ_+	
	$x_{.25}$ Series	$x_{.75}$ Series	Trials 1–6	Trials 7–32	Trials 1–6	Trials 7–32
100	65	135	5	3	15	9
200	130	270	9	6	27	18
400	300	500	15	10	45	30
600	440	760	25	17	75	51
800	500	1,100	70	22	210	66
1,000	500	1,500	100	25	300	75

All data are in milliseconds

comparison interval was randomized and balanced, with each interval being presented first in 50 % of the trials. Within each trial, the two intervals were presented with an interstimulus interval of 900 ms. The participant's task was to decide which of the two intervals was longer and to indicate his or her decision by pressing one of two designated response keys. After each response, visual feedback ("+" [i.e., correct] or "–" [i.e., false]) was displayed on the computer screen. The next trial started 900 ms after the feedback. Participants were not informed that a constant standard interval and a variable comparison interval were presented in every trial.

As an indicator of discrimination performance, the DL was determined. For this purpose, the mean differences between standard and comparison intervals were computed for the last 20 trials of each series. Thus, estimates of $c_{.25}$ and $c_{.75}$ of the individual psychometric functions were obtained in relation to the respective standard intervals. The data from Trials 1–12 were not analyzed because the initial stimulus level (i.e., the difference between standard and comparison) may have been too far away from the individual $c_{.25}$ and $c_{.75}$ points to be estimated, and furthermore, performance on early trials is generally considered too variable to yield reliable performance estimates (Levitt, 1971). In a second step, half of the interquartile range representing the DL (Luce & Galanter, 1963) was determined for each base duration. Superior performance on duration discrimination is indicated by smaller DL values. For enhancing the presentation of results, Weber fractions (i.e., DL/standard interval) were computed and analyzed instead of absolute DL values (see Killeen & Weiss, 1987; Rammsayer & Grondin, 2000).

Results

Weber fractions as a function of type of interval, sensory modality, and base duration are depicted in Fig. 1 separately for the 2AFC and reminder tasks. Visual inspection of Fig. 1 suggests highly similar effects of all structural aspects under investigation with both types of task. At the same time, however, temporal sensitivity appeared to be consistently higher with the reminder than with the 2AFC task, as is indicated by smaller Weber fractions.

A four-way analysis of variance revealed statistically significant main effects of sensory modality [$F(1, 184) = 116.94$, $p < .001$, $\eta_p^2 = .389$], type of task [$F(1, 184) = 49.15$, $p < .001$, $\eta_p^2 = .211$], and base duration [$F(5, 920) = 71.46$, $p < .001$, $\eta_p^2 = .280$]. The significant main effect of sensory modality indicated better discrimination performance with auditory than with visual intervals; the mean (± *SEM*) Weber fractions were 0.14 ± 0.006 and 0.23 ± 0.006 for auditory and visual intervals, respectively. The reliable main effect of type of task was due to larger DL estimates for the 2AFC than for the reminder task; the mean Weber fractions were 0.21 ± 0.006 and 0.15 ± 0.006 for the 2AFC and reminder tasks, respectively. Furthermore, Weber fractions differed significantly as a function of base duration. Post-hoc Tukey's HSD tests indicated that relative temporal sensitivity was much worse for the 100-ms base duration than for all longer base durations, and for the 200-ms base duration in comparison with base durations ranging from 600 to 1,000 ms (*p*s < .001 for all comparisons). No other differences in Weber fractions reached the 5 % level of statistical significance.

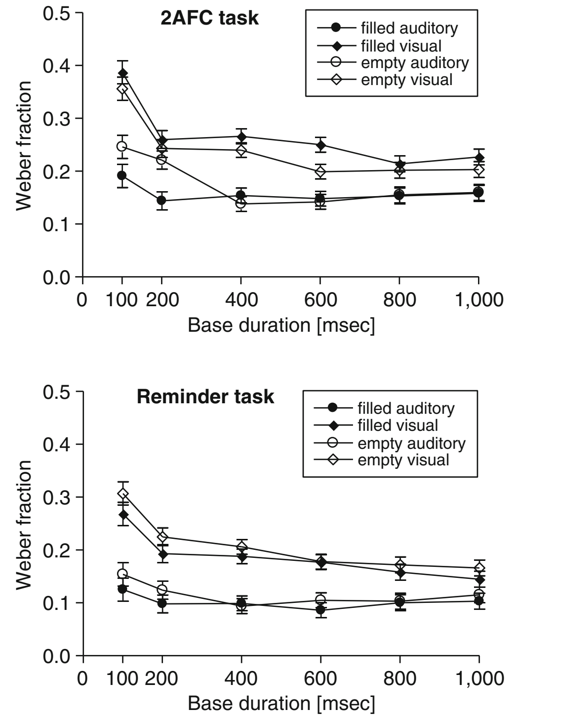

Fig. 1 Weber fractions (± standard errors) as a function of type of interval, sensory modality, and base duration, as obtained with the two-alternative forced-choice (2AFC; upper panel) and reminder (lower panel) tasks

No main effect of type of interval on discrimination performance could be established [$F(1, 184) = 0.66$, $p = .42$, $\eta_p^2 = .004$]; the mean Weber fractions for filled (0.18 ± 0.006) and empty (0.19 ± 0.006) intervals were virtually identical. However, a statistically significant two-way interaction between type of interval and base duration was apparent [$F(5, 920) = 3.32$, $p < .05$, $\eta_p^2 = .018$]. As is depicted in Fig. 2, this significant interaction indicated that performance on duration discrimination with filled and empty intervals was effectively moderated by base duration. With both types of interval, discrimination performance was significantly impaired for the 100-ms base duration relative to the longer base durations (*p*s < .001 for all comparisons). A statistically significant difference in discrimination performance as a function of base duration was also found for the 200-ms empty standard interval as compared to the 400-ms ($p < .01$), as well to the 600-, 800-, and 1,000-ms (*p*s < .001 for all comparisons), empty standard intervals. No such effect could be shown for filled

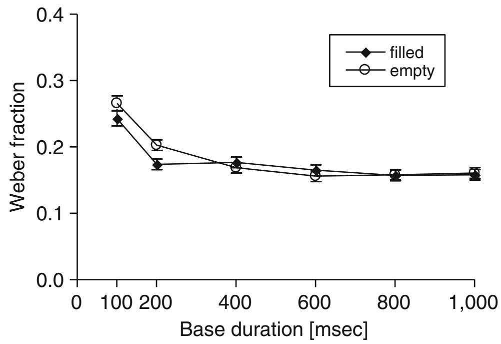

Fig. 2 Performance on duration discrimination, indicated by Weber fractions (± standard errors), as a function of type of interval (filled vs. empty) for base durations ranging from 100 through 1,000 ms

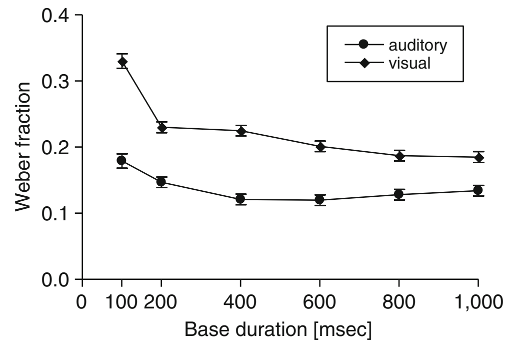

Fig. 3 Performance on duration discrimination, indicated by Weber fractions (± standard errors), as a function of sensory modality (auditory vs. visual) for base durations ranging from 100 through 1,000 ms

intervals. This pattern of results suggests that, with filled intervals, the deteriorating effect of base duration was limited to very brief base durations not exceeding 100 ms, whereas, in the case of empty intervals, temporal discriminability was adversely affected also for base durations as long as 200 ms.

Another statistically significant two-way interaction was confirmed for sensory modality and base duration [$F(5, 920) = 16.84$, $p < .001$, $\eta_p^2 = .084$]. Within the visual domain, post-hoc Tukey tests yielded impaired temporal sensitivity, as was indicated by significantly higher Weber fractions for the 100-ms base duration than for the longer base durations ranging from 200 to 1,000 ms (*p*s < .001 for all comparisons); for the 200-ms base duration than for the 600-ms ($p < .05$) and the 800- and 1,000-ms (*p*s < .001) base durations; and for the 400-ms base duration than for the 800- and 1,000-ms base durations ($p < .001$). For the auditory modality, however, a statistically significant difference in Weber fractions could only be established for the 100-ms base duration; performance on duration discrimination was considerably worse for the 100-ms base duration than for the 200-ms ($p < .05$) and all longer base durations (*p*s < .001 for all comparisons). In addition, post-hoc analyses also revealed significantly better performance on duration discrimination for auditory than for visual intervals at each of the six base durations (*p*s < .001 for all comparisons). Although still statistically significant, this modality-dependent difference in temporal sensitivity became noticeably reduced for base durations longer than 600 ms, where it appeared to level off (see Fig. 3). No other interactions reached the 5 % level of statistical significance.

Discussion

The present study was designed to further explore the influence of type of psychophysical task (2AFC and reminder task) as well as type of interval (filled vs. empty), sensory modality (auditory vs. visual), and base duration (ranging from 100 through 1,000 ms) as three structural aspects on performance on duration discrimination. Unlike previous studies, all these factors were systematically varied in a single, large-scale experiment. This approach enabled us to obtain important information not only on the general (main) effect of each factor alone but also on the functional interplay of these factors as indicated by their mutual interactions.

Statistically significant main effects indicated that, when seen on its own, sensory modality, type of task, and base duration clearly influenced duration discrimination performance. Consistent with previous studies, temporal sensitivity was markedly higher for auditory than for visually presented intervals, as well as for the reminder than for the 2AFC task. With regard to base duration, relative temporal sensitivity, as reflected by the Weber fraction, increased significantly from the 100- to the 200-ms base duration and remained constant for longer base durations. There was no indication, however, that performance on duration discrimination was influenced by type of interval except for extremely brief intervals; as a matter of fact, overall temporal sensitivity was virtually identical for filled and empty intervals.

Type-of-interval issue

In view of the large number of apparently inconsistent results on duration discrimination with filled and empty intervals (for concise reviews, see also Grondin, 2001, 2003, 2008; Penney, 2003; Rammsayer, 2010), the latter finding clearly argues for the assumption that there is no general difference in performance on duration discrimination between both types of intervals as long as sensory modality and type of task were held constant. The statistically significant interaction between type of interval and base duration indicated, however, that, at very brief base durations, empty intervals were more prone to a performance decrement than filled intervals: for filled intervals, the deteriorating effect of base duration was limited to base durations not exceeding 100 ms, whereas in the case of empty intervals, temporal discriminability was already affected at base durations as long as 200 ms.

Two often-quoted studies on the effects of filled and empty intervals on duration discrimination were conducted by

Grondin (1993; Grondin et al., 1998). In these two studies, findings were rather inconsistent though. This, however, is the expected outcome, given the results of the present study, in which type of task, sensory modality, and base duration were shown to exert effects on duration discrimination largely independent from each other. In his Experiments 1 and 3, Grondin (1993) found superior performance on duration discrimination for empty realtive to filled intervals with a mean base duration of 250 ms and applying either the method of single stimuli or a forced-choice procedure. In Experiment 4, however, no statistically significant difference between filled and empty intervals could be shown with the same base duration and an adaptive 2AFC task. Although the latter finding is consistent with the outcome obtained with the reminder task and 2AFC task in the present study, the filled-empty difference observed in Experiments 1 and 3 may be indicative of a differential effect of task in the case of the method of single stimuli and the non-adaptive forced-choice procedure applied by Grondin (1993, Exps. 1 and 3). Converging evidence for such a conclusion is provided by the finding of better discrimination performance for empty than for filled intervals obtained with the single-stimulus method and base durations of 375 and 750 ms (Grondin et al., 1998, Exp. 2). Even though, when applying an adaptive 2AFC task, empty intervals were better discriminated than filled intervals at a base duration of 400 ms, no such difference was found at a base duration of 800 ms (Grondin et al., 1998, Exp. 1). Thus, with an adaptive 2AFC task, filled–empty differences appear more unlikely to occur than with the method of single stimuli or a forced-choice procedure, especially in the case of longer base durations.

At first glance, in Experiment 1 (Grondin et al., 1998) and Experiment 4 (Grondin, 1993), type of task (i.e., an adaptive 2AFC task), sensory modality (i.e., auditory or visual), type of interval (filled and empty), and base duration (within the range of 100 to 1,000 ms) seemed to be identical to the ones employed in the present study. When taking a closer look, however, several crucial differences become apparent. Among others, these differences referred to the adaptive 2AFC tasks, the signals marking the empty intervals, and differences in the experimental design (e.g., between- vs. within-subjects design). All these factors may have contributed to the observed differences between Grondin's (1993, Exp. 4; Grondin et al., 1998, Exp. 1) findings and the outcome of the present study.

Weber fraction issue

The differential effect of base duration on duration discrimination with filled and empty intervals can be explained within two conceptual frameworks referred to as the *generalized form of Weber's law* and the *misassignment hypothesis*, respectively. The generalized form of Weber's law represents a major principle of time psychophysics (see Killeen & Weiss, 1987; Rammsayer & Grondin, 2000), which assumes a constant sensory noise that interferes with the genuine timing process. Thus, the constant sensory noise represents a duration-independent source of timing variability whose influence wears off with increasing base duration. At very short base durations, however, this noise component inflates total timing variance and, thus, leads to higher Weber fractions. Getty (1975) provided experimental evidence for the validity of the generalized form of Weber's law for duration discrimination with empty auditory intervals. He demonstrated that Weber's law, in its strict form, holds for the discrimination of durations ranging from 200 to 2,000 ms (but see also Grondin, 2012). With shorter durations, however, Weber fractions increased rapidly as predicted by the generalized form of Weber's law. The present data not only replicated Getty's findings, but also expanded them by showing that the generalized Weber's law also holds for *filled auditory* as well as for filled and empty visual intervals. Although, with empty intervals, a significant increase in Weber fractions could be observed for both the 100- and 200-ms base durations, this deteriorating effect was limited to the 100-ms base duration in the case of filled intervals. This may be indicative of a more-pronounced interfering effect of duration-independent sensory noise on the timing of empty than of filled intervals.

This theoretical account is further complemented by the misassignment hypothesis (Kallman, Beckstead, & Cameron, 1988; Kallman, Hirtle, & Davidson, 1986). This hypothesis proceeds from the notion that timing variability results from misassignment of pulses generated by an internal pacemaker. According to the process model of psychological timing described by Church (1984; Gibbon & Church, 1984), the internal clock is composed of a pacemaker, a switch, and an accumulator. The pacemaker generates pulses that are switched into the accumulator. The switch can be operated in different modes, some much more complex than others. The simplest switch mode, in which the switch is "on" at the onset of a signal and "off" at the offset of a signal, is applied to filled-interval trials, whereas a more complex mode is applied to empty-interval trials (see Rammsayer & Lima, 1991). Unlike filled intervals, empty intervals require the processing of four events—that is, onsets and offsets of the sensory markers bounding the interval—whereas no signal is present during the interval itself. If a more complex mode is more prone to error than the simplest switch mode, it should be the case that empty intervals are processed less accurately than filled intervals. In terms of the generalized Weber's law, the more complex switch mode associated with temporal processing of empty intervals could be perceived as a constant sensory noise. In accordance with the generalized form of Weber's law, this duration-independent source of additional variability in the timing process exerts a strong effect at extremely brief base durations. With increasing base duration, however, this interfering influence declines and is no longer effective at base durations exceeding 200 ms.

In a previous study, Rammsayer (2010) assessed performance on duration discrimination with filled and empty *auditory* intervals for base durations ranging from 50 to 1,000 ms. In this latter study, differences in temporal discriminability between filled and empty auditory intervals were confined to a 50-ms base duration. For such extremely brief intervals, performance on duration discrimination was reliably better with filled than with empty auditory intervals. In the present study, no 50-ms base duration condition was employed, because the outcome of a preceding pilot study had cast strong doubt on the validity of our *visual* duration discrimination task with empty intervals in the 50-ms range. In an unpublished experiment with 32 participants, performance on duration discrimination was assessed for filled and empty intervals in both the auditory and visual modalities employing a standard duration of 50 ms. In the auditory domain, filled intervals were discriminated significantly better than empty ones. In the visual domain, however, discrimination performance was significantly better with empty than with filled intervals (for more information, see the Appendix). Although the finding of superior discrimination performance for filled as compared to empty *auditory* intervals with a base duration shorter than 100 ms was consistent with the outcomes of a large number of previous studies also using auditory intervals (e.g., Abel, 1972a, 1972b; Rammsayer, 2010; Rammsayer & Altenmüller, 2006; Rammsayer & Brandler, 2004; Rammsayer & Lima, 1991; Rammsayer & Skrandies, 1998), the opposite finding for the visual intervals was rather unforeseen. When asked after the experiment whether they had used any strategies to enhance discrimination performance, most of the participants said that their judgments for the empty visual intervals were primarily based on perceived fusion rather than perceived duration. Perceived fusion provided a salient cue for the shorter of the two intervals to be compared and, thus, represented a highly efficient auxiliary strategy, especially in the case of extremely brief base durations. Given a visual fusion threshold of approximately 30 ms (Rammsayer et al., 2012), with empty intervals marked by two visual 3-ms flashes, comparison intervals shorter than the 50-ms standard interval could easily reach a temporal range in which fusion was perceived. Thus, by applying a fusion strategy, participants identified as shorter whichever interval appeared to be more fused. Implementation of such an auxiliary strategy could have been additionally encouraged by the correctness feedback presented at the end of each trial. It is important to note that a fusion strategy was unlikely to become effective with auditory intervals. This is because of the much lower fusion threshold of approximately 7 ms for the auditory domain (Rammsayer & Brandler, 2002, 2007; Rammsayer et al., 2012).

Modality issue

The observed main effect of Sensory Modality basically endorsed the ubiquitous finding of better temporal resolution in the auditory than in the visual domain (for reviews, see Penney & Tourret, 2005; van Wassenhove, 2009) as well as previous findings from duration discrimination experiments (e.g., Grondin, 1993; Grondin et al., 1998; Rammsayer et al., 2012; Stauffer et al., 2012; Ulrich et al., 2006). The statistically significant interaction between sensory modality and base duration, however, indicated that, for base durations shorter than 600 ms, auditory–visual performance differences in temporal discrimination increased with decreasing base duration. This effect was mainly brought about by a much more pronounced decrement in temporal sensitivity for visual than for auditory intervals with decreasing base duration. For base durations longer than 600 ms, temporal sensitivity was still better for auditory than for visual intervals, but this difference appeared to level off.

Higher temporal sensitivity for brief intervals in the auditory relative to the visual modality can be accounted for by at least three different explanatory approaches. First, higher auditory temporal sensitivity may be due to more efficient and more veridical processing of auditory than of visual information. This general approach is supported by slower response times (e.g., Brebner & Welford, 1980; Goldstone, 1968; Woodworth & Schlosberg, 1954) and larger response-time variability (e.g., Ulrich & Stapf, 1984) for visual than for auditory stimuli.

The observed modality-dependent differences in duration discrimination performance could also be explained within the framework of neural counting models of time perception (e.g., Creelman, 1962; Rammsayer & Ulrich, 2001; Treisman, 1963). According to this account, a neural pacemaker generates pulses and the number of pulses relating to a physical time interval is the internal (subjective) representation of this interval. The higher the pulse rate, the better the temporal resolution of the timing mechanism will be. Thus, the neural basis of better timing performance with auditory than with visual intervals can be envisioned as an increase in neural firing rate in the case of auditory temporal intervals (Grondin, 2001; Wearden, Edwards, Fakhri, & Percival, 1998). This higher pulse rate yields finer temporal resolution and, thus, less uncertainty about interval duration with auditory than with visual stimuli.

Eventually, the auditory–visual difference in duration discrimination may also point to modality-specific mechanisms for the timing of brief intervals. Indirect evidence for the notion of distinct mechanisms for the temporal processing of auditory and visual information, respectively, can be derived from the failure to demonstrate crossmodal perceptual learning in duration discrimination. Lapid et al. (2009) examined perceptual learning from the auditory to the visual modality. More specifically, they investigated if training on an auditory duration discrimination task facilitates the discrimination of visual durations with a base duration of 100 ms. No crossmodal training effect could be found. Similarly, Grondin, Bisson, Gagnon, Gamache, and Matteau (2009), using base durations in the 200-ms range, also arrived at the conclusion that little is to be expected from auditory training for improving visual duration discrimination. The outcome of both these studies favor the idea of two distinct modality-specific mechanisms for the processing of auditorily and visually presented temporal intervals. Additional converging evidence for the notion of two modality-specific timing mechanisms provided a recent psychophysiological study (Chen, Huang, Luo, Peng, & Liu, 2010) that revealed functional differences between auditory and visual temporal information processing by applying a duration-dependent mismatch negativity paradigm with a 200-ms standard interval.

Unlike very brief base durations below 600 ms, the auditory–visual difference in duration discrimination, although still present, appeared to level off at longer base durations. This overall pattern of results may be indicative of a transition from a purely modality-specific to a more amodal timing mechanism for the temporal processing of longer intervals. Indirect evidence for such a notion comes from a recent study applying a structural equation modeling approach to identify the relation between auditory and visual temporal processing in the subsecond range (Stauffer et al., 2012). In this study, a hierarchical process model with modality-specific auditory and visual temporal processing at an initial level and a modality-independent, amodal processing system at a second level described the empirical data much better than a model assuming a single modality-independent timing mechanism or a model based on the assumption of two independent modality-specific timing mechanisms. Within the framework of such a hierarchical model, it appears conceivable that extremely brief intervals are primarily processed at the initial modality-specific level, whereas with increasing interval duration, the amodal, modality-independent processing system progressively contributes to the timing process. Unfortunately, no other studies seem to exist associating the structure of temporal processing with modality-dependency. Only one study, by Merchant, Zarco, and Prado (2008), has, in the widest sense, suggested a similar structure for the processing of time. They used interval- and motor-timing tasks presented in the auditory and the visual modality with base durations ranging from 350 to 1,000 ms. On the basis of regression analyses, they proposed a model of partially overlapping timing mechanisms. According to their model, sensory modality-specific information is probably processed at the initial processing level, whereas the remaining aspects of a given timing task are processed by a common largely distributed neural system for the processing of temporal information.

Task issue

There is converging evidence for the notion that type of the psychophysical task applied for quantification of duration discrimination performance effectively influences the results. Lapid et al. (2008) compared the DL estimates from a 2AFC and a reminder task. The 2AFC task yielded DL estimates almost twice as high as the reminder task, a finding that has been previously replicated for auditory and visual filled intervals (Rammsayer & Ulrich, 2012) as well as for empty intervals (Grondin & McAuley, 2009). The present study confirmed that this task-specific effect is independent of base duration and holds for filled and empty intervals as well as for both the auditory and visual sensory modality. Although the ultimate reason why the 2AFC task produces larger DLs than does the reminder task is not completely understood yet, Ulrich and Vorberg's (2009) work strongly suggests so-called Type A and Type B order errors to underlie this type-of-task effect. Although the Type A order error reflects a consistent shift of the psychometric function due to a constant error or a response bias, the Type B order error is assumed to be caused by the presentation order of the standard and comparison interval and, thus, represents a genuine decline in sensitivity elicited by a perceptual interaction between successively presented stimuli (Ulrich, 2010).

As a conceptual framework to account for the observed differences between the reminder and the 2AFC task due to the Type B order error, the internal reference model (IRM; Dyjas, Bausenhart, & Ulrich, 2012; Lapid et al., 2008) has been introduced. According to this model, a virtual standard or internal reference is established and updated on every trial. In a recent validation study (Dyjas et al., 2012), IRM correctly predicted better discrimination performance, as indexed by DL, for the reminder as compared to the 2AFC task. Because the dynamic updating process proposed by the IRM could be considered a memory updating of sorts, IRM is consistent with the notion of a differential involvement of working memory in the reminder task and 2AFC task, respectively (Dyjas & Ulrich, 2013).

Conclusion

To sum up, the present study identified type of psychophysical task, sensory modality, and base duration as three largely independent sources of variance of duration discrimination in the subsecond range, whereas no general effect of type of interval could be established. Temporal sensitivity was significantly better when obtained with the reminder task than with the 2AFC task. This task-dependent effect held independent of type of interval, sensory modality, and base duration. Furthermore, temporal sensitivity was negatively affected when using visual rather than auditory intervals, or when using base durations of 200 ms or shorter rather than longer ones. This latter detrimental effect became even more pronounced when either empty intervals or visual intervals were employed. The absence of a statistically significant three-way interaction of base duration, type of interval, and sensory modality argued against the notion of an even more enhanced impairing effect when brief base durations and empty visual intervals were combined. Rather, this absent three-way interaction suggests two qualitatively different processes associated with the processing of filled and empty intervals, on the one hand, and auditory–visual differences, on the other one. Both these processes, however, appeared to be effectively moderated by base duration.

Appendix

Because of a lack of prior experience with extremely brief empty visual intervals (i.e., base durations shorter than 100 ms), a pilot study was performed to verify that the step sizes and initial values of the comparison intervals used for empty auditory intervals were also suitable for empty visual ones. The participants were 16 male and 16 female student volunteers, ranging in age from 18 to 28 years (mean age 22.7 ± 2.7 years). A within-subjects design was applied, with Type of Interval (filled and empty) and Sensory Modality (auditory and visual) as the two repeated-measures factors. The apparatus and stimuli were the same as in the main study, with the exception that only a single base duration of 50 ms was used. An adaptive 2AFC task identical to the one used in the main study was applied. The standard interval was 50 ms, and the initial values of the comparison interval were 65 and 35 ms for the $c_{.75}$ and the $c_{.25}$ series, respectively. The step sizes Δ_+ and Δ_- were 9 and 3 ms for Trials 1–6, and 6 and 2 ms for Trials 7–32 (see the Procedure section of the main study). As an indicator of discrimination performance, the DL was determined.

A two-way analysis of variance yielded statistically significant main effects of type of interval [$F(1, 31) = 13.89$, $p < .001$, $\eta_p^2 = .309$] and sensory modality [$F(1, 31) = 45.80$, $p < .001$, $\eta_p^2 = .596$], indicating superior performance on duration discrimination with empty (DL = 15.4 ± 5.1 ms) as compared to filled (DL = 19.1 ± 5.9 ms) intervals, and for the auditory (DL = 14.2 ± 4.6 ms) as compared to the visual (DL = 20.3 ± 6.1 ms) modality. Most importantly, however, a significant interaction of type of interval and sensory modality was also found [$F(1, 31) = 234.91$, $p < .001$, $\eta_p^2 = .883$]. Post-hoc Tukey tests revealed reliably better discrimination performance ($p < .001$) for filled (DL = 8.1 ± 3.0 ms) than for empty (DL = 20.3 ± 7.6 ms) intervals within the *auditory* modality, but significantly better performance ($p < .001$) for empty (DL = 10.6 ± 4.4 ms) than for filled (DL = 30.0 ± 9.8 ms) intervals in the *visual* domain.

When asked after completion of the experiment whether they had used any strategies to solve the discrimination tasks, 24 of the participants indicated that their judgments for the empty visual intervals were primarily based on perceived fusion rather than perceived duration. When comparing the DL values of those participants who applied a fusion strategy to those of participants who did not, a *t* test revealed significantly better discrimination performance for the former than for the latter group [$t(30) = 6.22$, $p < .001$]; the mean DL values were 8.9 ± 2.6 ms and 16.3 ± 3.9 ms for participants who applied and who did not apply a fusion strategy, respectively. No significant differences in DL values between these two groups could be shown for the other three duration discrimination tasks. This pattern of results suggests that the discrimination of empty visual intervals clearly benefited from the perceived-fusion strategy, whereas performance on the other duration discrimination tasks was not affected.

Although the majority of participants profited from using a fusion strategy for temporal discrimination of empty visual intervals, also in those participants who did not use a fusion strategy, performance on duration discrimination was significantly better with empty than with filled visual intervals [$t(7) = 4.70$, $p < .05$]. This finding suggests better duration discrimination with empty than with filled visual intervals, regardless of the timing strategy applied. Converging evidence for such an interpretation comes from two experiments reported by Grondin (1993). In a first experiment (Grondin, 1993, Exp. 2), participants had to discriminate between a 50- and an 80-ms visual interval, according to the method of single stimuli. Their mean probability of correct responses was significantly higher for empty than for filled visual intervals. In a second experiment (Grondin, 1993, Exp. 4), an adaptive forced-choice procedure was used with a base duration of 50 ms and variable comparison intervals longer than 50 ms. Again, discrimination performance, as indicated by the 75 %-difference threshold, was significantly better with empty than with filled visual intervals. In both of these experiments, all comparison durations were longer than the 50-ms base duration. Therefore, in contrast to the present pilot study, it appears rather unlikely that Grondin's participants used a fusion strategy. As a theoretical account for the superior temporal accuracy with extremely brief empty *visual* intervals, relative to filled ones, Grondin (1993) introduced the internal-marker hypothesis. Although this theory is highly attractive for its simplicity, it remains unclear how the hypothesis can account for the finding of better duration discrimination with filled than with empty *auditory* intervals (see Rammsayer, 2010).

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