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Duration perception of visual and auditory oddball stimuli: Does judgment task modulate the temporal oddball effect?

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Abstract The duration of rare stimuli (oddballs) presented within a stream of homogenous standards tends to be overestimated. This temporal oddball effect (OE) has been attributed to perceptual processes. The OE is usually assessed with a comparative judgment task. It has been argued, however, that this task is prone to decision biases. The present experiments employed comparative and equality judgments, since it has been suggested that equality judgments are less vulnerable to such biases. Experiments 1a and 1b used visual stimuli, and Experiment 2 auditory stimuli. The results provide no strong evidence for decision biases influencing the OE. In addition, computational modeling clearly suggests that the equality judgment is not particularly suited to distinguish between perceptual and decisional effects. Taken together, the pattern of the present results is most consistent with a perceptual origin of the OE.

Keywords Decision making · Temporal processing

The perception of time is prone to distortions and illusions (e.g., Eagleman, 2008). One reason for that might be that the human organism lacks a sensory system for the physical quantity *time*. In contrast to visual or auditory events, where specialized receptors transfer the physical input into sensory impression, duration information needs to be inferred by internal processes (e.g., an internal clock). These underlying processes of time perception and the factors influencing and distorting it have been the focus of many psychophysical studies conducted over the past few decades (for an overview, see Eagleman, 2008; Grondin, 2001b, 2010). These studies have shown that temporal judgments about the duration of stimuli are also affected by the stimuli's nontemporal features. For example, unexpected stimuli are often perceived as lasting longer than others of the same physical duration. This phenomenon of "time's subjective expansion" (Tse, Intrilligator, Rivest, & Cavanagh, 2004) or "time dilation" (New & Scholl, 2009; van Wassenhove, Buonomano, Shimojo, & Shams, 2008) of rare stimuli has been termed the *temporal oddball effect* (OE; Pariyadath & Eagleman, 2007; Schindel, Rowlands, & Arnold, 2011).[1]

In a typical temporal oddball paradigm, an infrequent deviant stimulus (oddball) is presented randomly within a stream of frequent, homogenous stimuli (standards). Importantly, the oddball varies clearly from the standards concerning a certain feature—for example, color or tone pitch—and is of varying duration, while standards are of constant duration. The participants' task is to judge the oddball duration in comparison with the standard duration, commonly by rating whether the oddball was "shorter" or "longer" than the standards (comparative judgment task; Chen & Yeh, 2009; Schindel et al., 2011; Tse et al., 2004). The proportion of "longer" judgments as a function of oddball durations is used to fit a psychometric function from which the point of subjective equality (PSE) is computed as a measurement of perceived duration. Using this procedure, it has been repeatedly documented that participants tend to overestimate the duration of oddballs, as is indicated by PSEs smaller than the standard duration (Chen & Yeh, 2009; New & Scholl, 2009; Schindel et al., 2011; Tse et al., 2004; Ulrich, Nitschke, & Rammsayer, 2006).

Specifically, Tse et al. (2004) investigated the OE in a series of experiments by presenting different types of visual oddballs (e.g., expanding black disks, black squares, colored disks)

[1] *Chronostasis* describes a related effect of temporal overestimation. Specifically, the first stimulus in a series of stimuli is often judged as being longer than the other stimuli (Hodinott-Hill, Thilo, Cowey, & Walsh, 2002; Rose & Summers, 1995; Yarrow, Haggard, Heal, Brown, & Rothwell, 2001; Yarrow, Haggard, & Rothwell, 2004).

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within a stream of homogeneous standards (e.g., solid black disks). OEs were observed irrespective of oddball type. The finding of an OE was replicated by several other authors using different experimental designs, although the size of the observed OEs was often smaller than the ones reported by Tse and colleagues (Schindel et al., 2011; Ulrich et al., 2006; van Wassenhove et al., 2008; see Seifried & Ulrich, 2010, for a possible explanation). In addition, it has been shown that the OE can be demonstrated not only for visual stimuli, but also for auditory ones (Tse et al., 2004; van Wassenhove et al., 2008).

The temporal OE has mostly been explained within the framework of internal clock models such as pacemaker–accumulator models of duration perception (Allan, 1998; Gibbon, 1991; Gibbon, Church, & Meck, 1984; Wearden, 1999, 2003; Zakay & Block, 1997). These models assume that pulses, constantly generated by a pacemaker, have to pass a switch in order to be collected and counted by an accumulator. The switch closes and opens with the on- and offset of a to-be-timed interval, and pulses can arrive at the accumulator only when the switch is closed. The more pulses that are accumulated during a given interval, the longer is the perceived duration. Following this logic, the OE emerges because more pulses are accumulated for an oddball than for a standard of identical physical duration.

Attention and arousal are often assumed to influence different processing stages of such pacemaker–accumulator models (e.g., Treisman, Faulkner, Naish, & Brogan, 1990; Zakay & Block, 1997). Therefore, some authors have argued that oddballs attract more attention than do standards and that attention increases the number of accumulated pulses in a given time interval (Schindel et al., 2011; Tse et al., 2004). This argumentation, however, is at variance with the attentional-gate model (Zakay & Block, 1997). This version of a pacemaker–accumulator model proposes an additional gate mechanism that modulates how many pulses emitted by the pacemaker arrive at the switch. According to this model, attention is divided between temporal and nontemporal information (see also, Fortin, 2003; James, 1890; Macar, Grondin, & Casini, 1994). The ratio of attention directed toward temporal features, on the one hand, and nontemporal features, on the other hand, modulates the opening of the gate. When attention is more strongly directed toward temporal aspects, the gate widens. Contrary, the gate narrows when attention is directed toward nontemporal features of an interval. Because oddball stimuli differ from standards in nontemporal aspects such as color or pitch, attention should be drawn toward those features rather than toward time. Consequently, fewer pulses should arrive at the switch and be collected in the accumulator. Thus, the attentional-gate model predicts an underestimation of oddballs, which is in contrast to the commonly observed OE.

In order to explain the oddball effect within pacemaker–accumulator models, one needs to assume that oddballs result in a higher number of collected pulses. For example, more pulses could be collected due to an earlier closing of the switch (Droit-Volet, 2003; Lejeune, 1998) or a lower probability of pulse loss (Fortin, 2003; Thomas & Weaver, 1975). Others have suggested that oddballs excite more arousal than do standards (Chen & Yeh, 2009; Ulrich et al., 2006), which is presumed to speed up the internal pacemaker, also resulting in more pulses being accumulated (Penton-Voak, Edwards, Percival, & Wearden, 1996; Zakay & Block, 1997).

Although the specific mechanisms underlying the OE are still under debate, there is a consensus that this effect originates at a perceptual level of information processing (e.g., Schindel et al., 2011; Tse et al., 2004; Ulrich et al., 2006). Nevertheless, it is still conceivable that the OE arises at a decisional level. This view is supported by arguments proposed by Schneider and Komlos (2008). They examined the influence of exogenous cues on the perception of two Gabor gratings. Participants judged the cued gratings as higher in contrast than the uncued ones if they were asked to perform a comparative judgment task. However, this effect disappeared if an equality judgment was required. In this task, participants were asked whether the two gratings were of “same” or “different” contrast. Schneider and Komlos observed that the PSE was shifted to the left from the point of objective equality for comparative judgments, whereas no shift in location was present for equality judgments. They explained these deviant findings by a decision bias operating in the comparative but not in the equality judgment task. Specifically, in their study, such a bias might have arisen in the comparative judgment task because for this task the PSE is commonly assessed at a point of maximal uncertainty—that is, the 50 % point of the psychometric function. Schneider and Komlos have argued that when participants are in such a state of maximal uncertainty, they might be tempted to base their judgment on a top-down decision rule that favors one over the other response alternative. In particular, these authors assumed that their participants tended to judge the cued grating as being larger in contrast whenever they were actually uncertain about the correct response alternative. This could have caused the observed PSE shift in the comparative judgment task. However, an analogous response rule in an equality judgment task (favoring “equal” over “unequal” responses) would influence only the height, but not the peak of the bell-shaped psychometric function. Consequently, Schneider and Komlos infer that attention does not alter contrast appearance and that former evidence interpreted accordingly (e.g., Carrasco, Ling, & Read, 2004) can be attributed to a judgment-dependent decision bias. Employing this approach in the field of speed perception, Valsecchi, Vescovi, and Turatto (2010) have shown that PSE effects based on comparative judgments indeed disappear when subjects perform the equality task instead.

Transferring this idea to the classical oddball paradigm, participants might fall back on a top-down decision rule whenever they experience oddball durations to be just as long as the standard duration. Such a decision rule could take the form of preferring the "longer" response whenever participants are uncertain about whether the oddball was actually shorter or longer than the standards. The resulting psychometric functions would be shifted to the left from standard duration. Whereas it is obvious that such a decision rule would influence the estimated PSE, it is less clear why participants should favor "longer" over "shorter" responses. Experiments examining asymmetries in the spontaneous use of different comparative adjectives (Matthews & Dylman, 2013) reported recently that participants generally favor "larger" responses over "smaller" responses. When the task is to compare two objects according to a certain dimension, participants apparently prefer to say "A is bigger/longer/higher than B", as compared with "B is smaller/shorter/lower than A". If there is a general preference for "longer" over "shorter" responses irrespective of the specific task, this could explain why participants adopt the aforementioned decision rule and how this could mimic a perceptual OE in the comparative judgment data.

On the basis of these considerations, it seems natural to test whether decision mechanisms might play a role in the emergence of the OE. Since the OE has only been studied using comparative judgments so far, it cannot be ruled out that the documented effect is the result of decisional processes, rather than a genuine time perception phenomenon. Hence, it is the aim of the present study to clarify whether the OE is the product of a decision bias. To this end, the standard oddball paradigm was used with visual (Experiments 1a and 1b) and auditory (Experiment 2) stimuli, and participants were asked to give both comparative and equality judgments. If the OE is due to effects on a perceptual level as proposed in previous studies, the OE should be present irrespective of the judgment task. However, if the OE reflected a decision bias provoked by the comparative judgment, the OE might disappear when equality judgments are given.

We manipulated not only the judgment task, but also the position of the oddball. Oddballs could appear at early, middle, or late positions within the series of standards. The effect of oddball position on the OE could provide additional insight into its origin. According to Matthews (2011) and Pariyadath and Eagleman (2012), a repetition suppression effect could also account for the OE, rather than a temporal expansion of the oddball. The idea is that the repeated presentation of the standards causes a reduction in the neural response and, hence, results in a shortened representation of the standard duration (see also Eagleman & Pariyadath, 2009; Noguchi & Kakigi, 2006). The OE would therefore be due to a subjectively shortened standard duration, rather than to a subjectively expanded oddball duration. This repetition suppression effect should increase as more standards are presented prior to the oddball. As a result, the size of the OE should increase with oddball position. This prediction was confirmed by the results of Pariyadath and Eagleman (2012). Recently, Kim and McAuley (2013) replicated this modulation of the OE by oddball position. These authors, however, explain this effect differently. They show that oddballs at later positions are detected more quickly and propose that this is due to greater temporal preparation for later occurring oddballs. This would shorten the perceptual latency (see Seifried, Ulrich, Bausenhart, Rolke, & Osman, 2010) and, thus, increase the OE at later oddball positions. Importantly, according to both accounts, a modulation by oddball position can be taken as additional evidence for a perceptual origin of the OE.

Experiment 1a

Experiment 1a used a typical oddball paradigm in which a stream of visual stimuli was presented. This stream comprised nine standards and one oddball; all the stimuli were small filled disks. The oddball differed from the standards with respect to color. The duration of the standards was always 500 ms, whereas oddball durations varied. Participants were asked to judge whether the oddball was shorter or longer than the standards (comparative judgment task) or whether the oddball was of the same duration as, or a different duration than, the standard duration (equality judgment task). If the OE emerges from nondecisional processes, it should be observed not only for the comparative judgment task, but also for the equality judgment task.

Method

Participants

Thirty-two students (24 female; 19–34 years, M = 22.5 years, SD = 3.8 years) from the University of Tübingen participated in the experiment. Twenty-seven of them were right-handed, and all had normal or corrected-to-normal visual acuity and normal color vision. The experimental session lasted about 1.5 h, and participants either received partial course credit or were paid € 12. Three additional students participated, but their data had to be excluded from analyses due to flat psychometric functions.

Apparatus and stimuli

The experiment was programmed in MATLAB® using the Psychophysics Toolbox 3 (Brainard, 1997). A personal computer controlled the stimuli presentation and recorded the participants' responses. The computer screen (standard VGA screen) had a resolution of 1,024 × 768 pixels and a refresh rate of 150 Hz. The left and right shift keys of a standard German keyboard served as response keys.

Filled red and blue circles (diameter 1.1° of visual angle) served as stimuli and were presented in the middle of a black computer screen. For half of the participants, standards were blue and oddballs were red; for the other half, colors were reversed. Luminance of both colors was matched to approximately 34 cd/m^2 (black < 0.1 cd/m^2). The standard stimuli were presented for a constant duration of 500 ms. Nine comparison durations were distributed in a physically symmetrical manner around the standard duration (Seifried & Ulrich, 2010). The comparison durations were 287, 340, 393, 447, 500, 553, 607, 660, and 713 ms. They were chosen to be integer numbers of screen refreshes.

Procedure

The experiment took place in a dimly lit and sound-attenuated room. Participants received written and verbal instructions before the experiment started. The experimental session was divided into one practice block and six experimental blocks. The practice block consisted of 18 trials; the experimental blocks had 54 trials each. Short breaks were integrated between the blocks and twice within the experimental blocks (every 18 trials) to give participants the opportunity to relax and refocus. All breaks could be terminated by the participant via a keypress.

Figure 1 shows a schematic trial procedure. On each trial, a stream of nine standard stimuli and one oddball stimulus were presented, one stimulus at a time, in the center of the screen. The oddball's position in the stream was the 4th, 5th, 6th, 7th, 8th, or 9th, so that at least three standards were presented previous to the oddball and the oddball was never the last stimulus in the stream. The oddball positions were balanced over the comparison durations. Each of the nine comparison durations appeared at each position, respectively, resulting in the experimental block length of 54 trials (6 positions × 9 durations). All stimuli were separated by an interstimulus interval (ISI) that varied randomly around 500 ms and ranged from 447 to 553 ms; the values were always rounded to the nearest number of screen refreshes. Variable ISIs were chosen to avoid a predictable rhythm that might influence the temporal perception incalculably. After the last standard stimulus and the following ISI, a response screen was shown including a small white question mark and reminders of the two response alternatives and their key assignments in the lower left and right corners. These reminders were the German words "kürzer" and "länger" ("shorter" and "longer") for the comparative judgment task and "gleich" and "ungleich" ("equal" and "not equal") for the equality judgment task. The response screen was terminated by a keypress of any response key. Afterward, the next trial started again with an ISI.

Participants were instructed to give a judgment about the oddball's duration. In half of the blocks, participants were asked to judge whether the oddball was shorter or longer than the standard stimuli (comparative judgment). In the other half of the blocks, they were asked to judge whether the oddball was of equal duration than the standard stimuli or of unequal duration (equality judgment). The judgment tasks alternated between blocks and were announced at the beginning of each block. Three experimental blocks required the comparative judgment task, and three experimental blocks required the equality judgment task. In the practice block at the beginning of the session, both judgment tasks were integrated. Additionally, the key assignment (e.g., left–shorter, right–longer) was announced prior to each block. Participants were informed that all standards were of constant duration and that only oddball durations varied. They were encouraged to use the standards shown previous to the oddball, as well as the ones presented afterward, in order to give their judgments.

Design

The point of subjective equality (PSE) was calculated from the relative frequencies of "longer" and "equal" judgments for the nine comparison durations. In total, there were 324 experimental trials (excluding the practice trials). Half of them required a comparative judgment, and the other half required an equality judgment. Three trials were run in each possible combination of oddball position and comparison duration (3 × 6 positions × 9 comparison duration) for both judgment tasks. Results concerning the oddball's position in the stream are shown for early (4th, 5th), middle (6th, 7th), and late (8th, 9th) positions in the stream to obtain more reliable estimates based on six, rather than only three, trials per combination of position and comparison duration. The color of oddballs (and standards, respectively), the order of judgment task (beginning with comparative or equality judgment), and the four possible key assignments (left–shorter/unequal, right–longer/equal; left–shorter/equal, right–longer/unequal; left–longer/unequal, right–shorter/equal; left–longer/equal, right–shorter/unequal) were counterbalanced across participants.

Dependent variables and data analysis

A variety of methods have been used in previous studies to calculate the PSE from the relative frequencies of "longer" and "equal" judgments (see Miller & Ulrich, 2001, for a comparison of methods). In the present study, the nonparametric Spearman–Kärber method (Miller & Ulrich, 2001) was used to identify the PSEs in the comparative judgment data. This method does not require specific assumptions about the distributional shape of the underlying psychometric function. Therefore, it provides more accurate estimates of location and dispersion parameters if the assumption of a cumulative normal distribution is violated, which can be the case for many reasons (Miller & Ulrich, 2001). We calculated

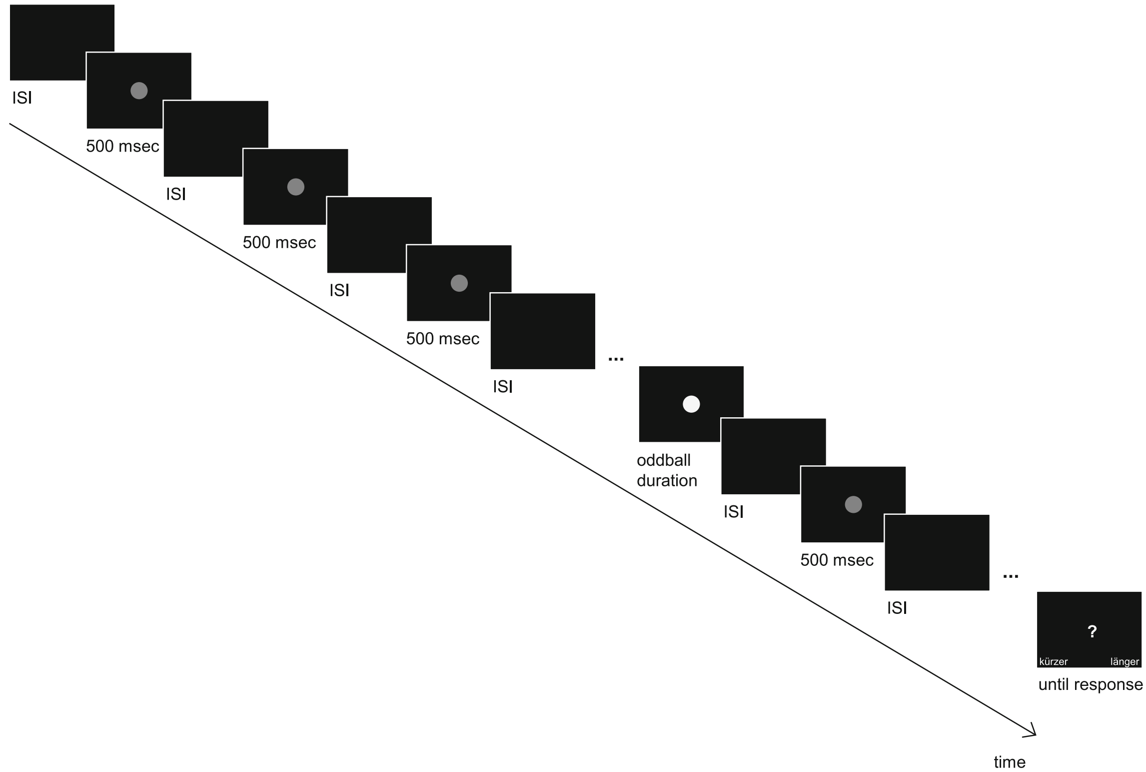

Fig. 1 Schematic illustration of the trial procedure in Experiment 1a and Experiment 1b. The gray circles represent the standard stimuli lasting for a fixed standard duration of 500 ms. The white circle indicates an oddball stimulus. Its duration changed from trial to trial. Stimuli were red and blue circles in the experiment. This illustration shows a sample trial of the comparative judgment task

individual location parameters equivalent to the PSE for each participant.

For the equality judgment data, the waveform moment analysis (Cacioppo & Dorfman, 1987) was adopted. First, the relative frequencies of an "equal" judgment of each participant (p_i) were transformed in a way that the new values (p_i^*) sum up to one, just like a probability function,

$$p_i^* = \frac{p_i}{\sum_{i=1}^{k} p_i}, \tag{1}$$

where k represents the number of comparison durations. From those transformed data, a mean value representing PSE was calculated as follows:

$$M = \sum_{i=1}^{k} p_i^* \cdot d_i, \tag{2}$$

where d_i are the objective comparison duration values and M indicates the PSE. Note that the two PSE values derived from the Spearman–Kärber method and from the waveform moment analysis are not strict equivalents and can, therefore, not be compared directly. This is uncritical because we were interested only in whether an OE occurred at all depending on judgment task. For both judgment tasks, the constant error (CE) was computed as the difference between the PSE and the standard duration (CE = PSE − standard).

Results and discussion

Figure 2 displays the relative frequencies of "longer" and "equal" judgments for the nine comparison durations averaged across all participants. An ideal observer would give a "longer" response in the comparative judgment task on 50.0 % of all trials, whereas he would give an "equal" response in the equality judgment task on only 11.1 % of all trials. In the present experiment, participants on average responded "longer" on 55.4 % of the comparative judgment trials and "equal" on 39.9 % of the equality judgment trials.

Individual PSEs and CEs were calculated for each condition as described above. An alpha level of .05 was set for all significance tests. To test whether significant OEs occurred, mean CEs resulting from both judgment tasks were tested separately against zero, using one-sample t-tests.

For the comparative judgment task, the PSE calculations yielded an average CE of −23 ms, which is indicative of a significant OE, $t(31) = 3.75$, $p < .001$. For the equality judgment task, a mean CE of −30 ms was computed, which was also significantly different from zero, $t(31) = 8.26$, $p < .001$. A direct comparison of both CE values is not permissible, as was mentioned above.

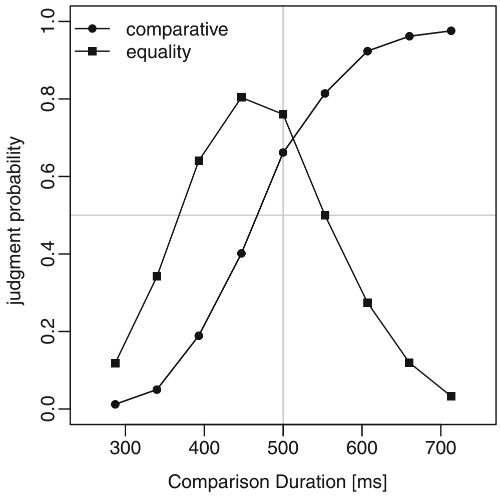

Fig. 2 Relative frequencies of "longer" judgments in the comparative judgment task (circles) and "equal" judgments in the equality judgment task (squares) as a function of oddball duration in Experiment 1a. Relative frequencies are collapsed over all participants

We additionally analyzed the effect of oddball position in the stream. Figure 3 shows the mean visual CEs as a function of judgment task and oddball position. One-factorial ANOVAs were conducted separately for the two judgment tasks. The first ANOVA revealed a significant effect of oddball position on CE in the comparative judgment task, $F(2,62) = 9.05$, $MSE = 384$, $p < .001$. Post hoc Tukey's HSD tests uncovered significant differences in CE between early ($M = -12$ ms, $SD = 43$ ms) and middle ($M = -33$ ms, $SD = 39$ ms) oddball positions and between early and late ($M = -25$ ms, $SD = 33$ ms) oddball positions, both at a $p < .05$ significance level. CEs did not differ significantly for middle and late oddball positions. The second ANOVA confirmed that oddball position did not influence the CE in the equality judgment task, $F < 1$.

Significant OEs were observed for both judgment tasks. Therefore, the OE seemed to emerge on a time perception level rather than on a decisional level. The results concerning the oddball position suggest that oddball position does influence the perceived duration of oddballs if measured by a comparative judgment, but not if measured by an equality judgment. Accordingly, equality judgments appear to be less sensitive to the oddball position than comparative judgments. Unfortunately, we cannot provide a reasonable explanation as to why equality judgments are less sensitive to oddball position than comparative judgments.

The present results suggest no involvement of a decision bias, because an OE occurred in both judgment tasks. However, it was suggested by a reviewer that carryover influences could be responsible for these findings. Because participants had to swap between comparative and equality judgments between blocks (i.e., after every 54 trials), they might have used a common decision rule, rather than performing the two tasks independently. To clarify whether the present result pattern could be attributed to carryover influences, we conducted a control experiment in which the judgment task was manipulated between subjects. Observing an OE in both tasks would provide strong evidence that the results of Experiment 1a do not reflect carryover effects.

Experiment 1b

Experiment 1b tests whether the similar results for the two judgment tasks observed in Experiment 1a might be the result

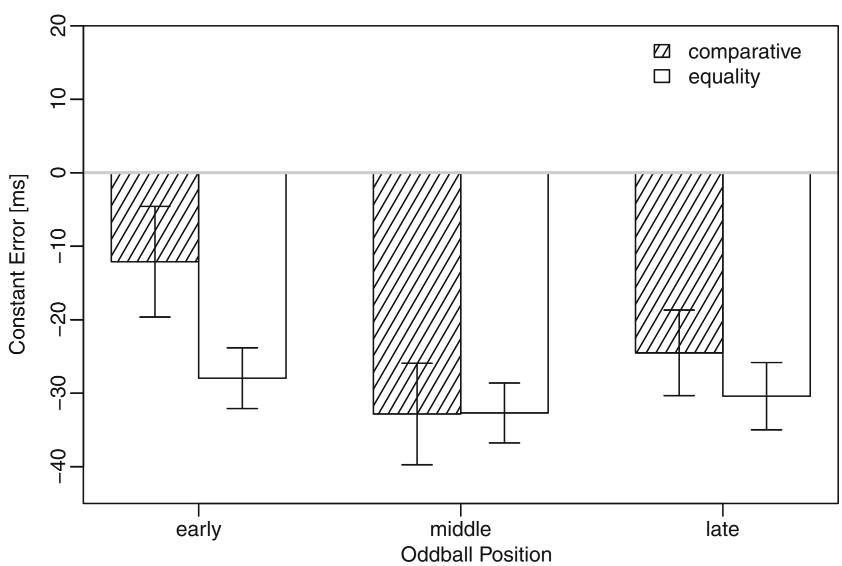

Fig. 3 Mean visual constant errors (CEs; CE = PSE – standard) separately for early, middle, and late oddball positions in the stream. Striped bars represent the comparative judgment task, and plain bars the equality judgment task in Experiment 1a. Error bars indicate ±1 standard error

of carryover influences due to the ongoing alternation of the two tasks. This experiment was identical to Experiment 1a, with one exception. The two judgment tasks were performed by separate groups of participants to prevent any potential interactions between the two tasks.

Method

Participants

A fresh sample of 32 participants from the University of Tübingen were recruited (25 female; 19–56 years, $M = 24.9$ years, $SD = 6.4$ years). Twenty-nine of them were right-handed, and all reported normal or corrected-to-normal vision and normal color vision. The participants were randomly assigned to the two judgment task groups. They received partial course credit or were paid € 6 for their participation. The data of 2 additional participants were excluded from analyses due to flat psychometric functions.

Apparatus, stimuli, and procedure

The apparatus, stimuli, and procedure were identical to those in Experiment 1a, with the following exceptions. The experimental session was divided into one practice block and three experimental blocks. Each participant performed 162 experimental trials in either the comparative or the equality judgment task (half of the total trials used in Experiment 1a).

Design, dependent variables, and analysis

The color of oddballs (and standards, respectively) and the two possible key assignments for each group (left–shorter, right–longer, and left–longer, right–shorter, for the comparative judgment group; left–unequal, right–equal, and left–equal, right–unequal, for the equality judgment group) were counterbalanced across participants. Dependent variables and data analyses were the same as in Experiment 1a.

Results and discussion

Figure 4 shows the mean relative frequencies of "longer" and "equal" judgments. On average, participants performing the comparative (equality) judgment task gave "longer" ("equal") responses in 57.5 % (52.9 %) of all trials.

The mean CE in the comparative judgment group was −33 ms, which was indicative of a significant OE, $t(15) = 5.50$, $p < .001$. The mean CE in the equality judgment group was −19 ms, which also differed significantly from zero, $t(15) = 3.11$, $p = .007$. Thus, a significant OE was present in both judgment groups. As in Experiment 1a, one-factorial ANOVAs were conducted to investigate possible effects of oddball position (see Fig. 5). No main effect of oddball position was present in the comparative judgment group, $F(2,30) = 2.40$, $MSE = 286$, $p = .108$, or in the equality judgment group, $F(2,30) = 2.41$, $MSE = 189$, $p = .107$.

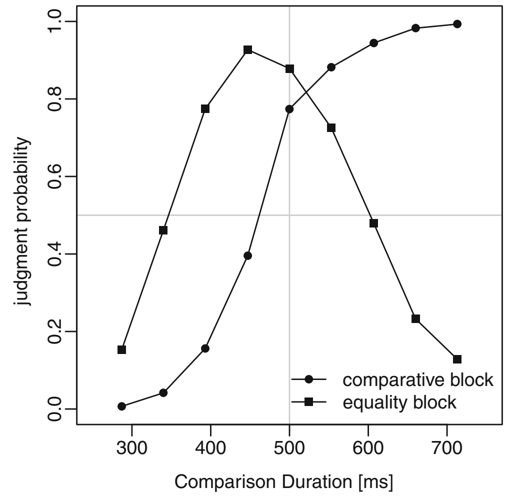

Fig. 4 Relative frequencies of "longer" judgments in the comparative judgment task performed by one half of the participants (circles) and "equal" judgments in the equality judgment task performed by the other half of the participants (squares) as a function of oddball duration in Experiment 1b. Relative frequencies are collapsed over all participants per group

Most important, an OE was observed irrespective of judgment task, replicating the main result of Experiment 1a. This finding provides strong evidence against the possibility that the OEs observed in Experiment 1a were a result of carryover influences. Instead, it further strengthens the notion that the OE emerges on a perception level rather than on a decisional level. Furthermore, the size of the OE in the comparative judgment task again tended to increase with oddball position (see Fig. 5), although this effect was not statistically reliable. This might be due to a lack of statistical power, because only 16 participants per group were tested.

Experiment 2

A judgment-independent OE was obtained in Experiments 1a and 1b, indicating that the OE is not based on a decision bias associated with the comparative judgment task. To test whether this finding can be replicated in a different modality, Experiment 2 employed auditory standards and oddballs, instead of visual ones, and used a design very similar to the one in Experiment 1a.

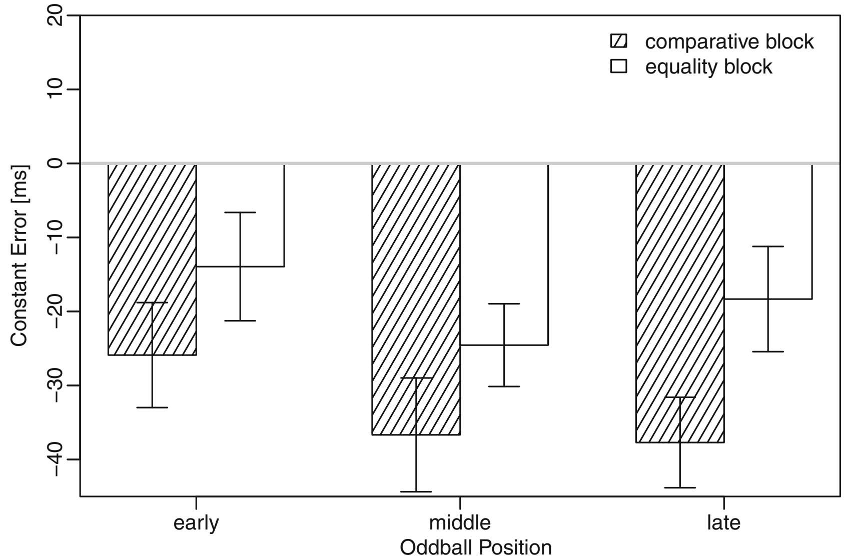

Fig. 5 Mean visual constant errors (CEs; CE = PSE – standard) separately for early, middle, and late oddball positions in the stream. Striped bars represent the data from the comparative judgment group, and plain bars the data from the equality judgment group in Experiment 1b. Error bars represent ±1 standard error

Method

Participants

A fresh sample of 32 students from the University of Tübingen participated in the experiment (27 female; 18–32 years, M = 21.7 years, SD = 3.3 years). Thirty-one of them were right-handed, and all reported normal hearing ability. Participants received partial course credit or were paid € 12 for their participation. The data of 1 additional participant had to be excluded from analyses due to flat psychometric functions.

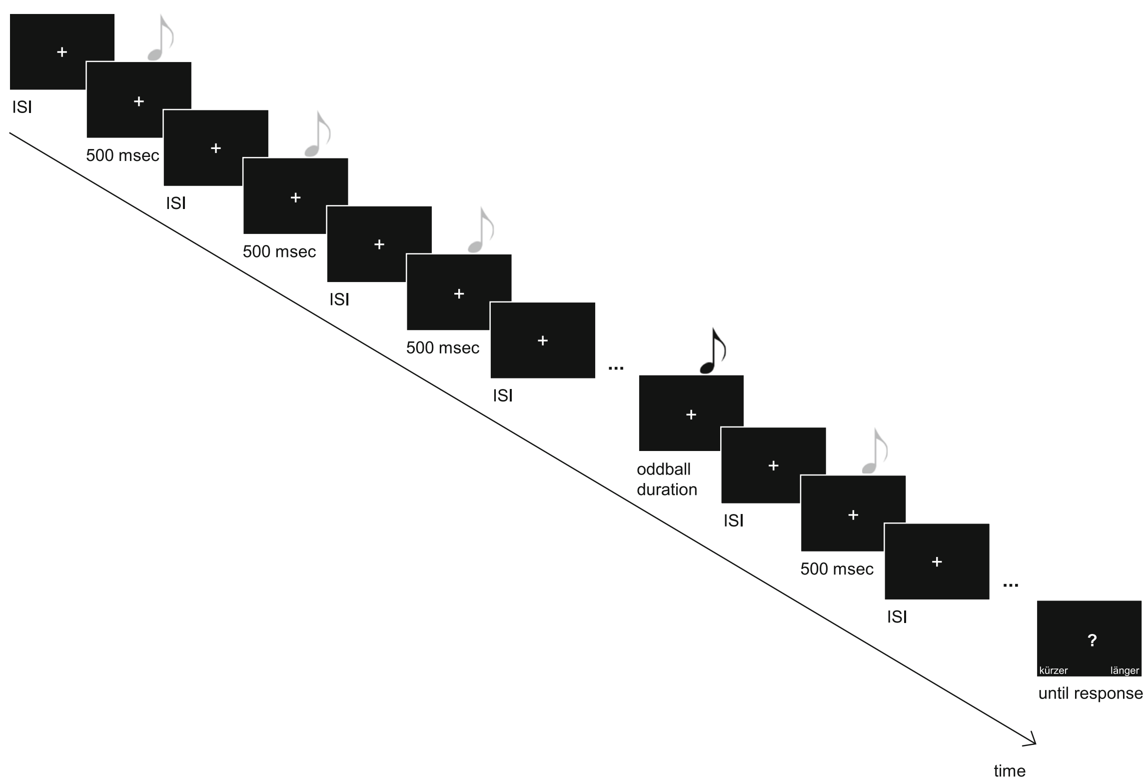

Fig. 6 Schematic illustration of the trial procedure in Experiment 2. The gray notes represent the standard stimuli lasting for a fixed standard duration of 500 ms. The black note indicates an oddball stimulus. Its duration changed from trial to trial. Stimuli were high- and low-pitch tones in the experiment. This illustration shows a sample trial of the comparative judgment task

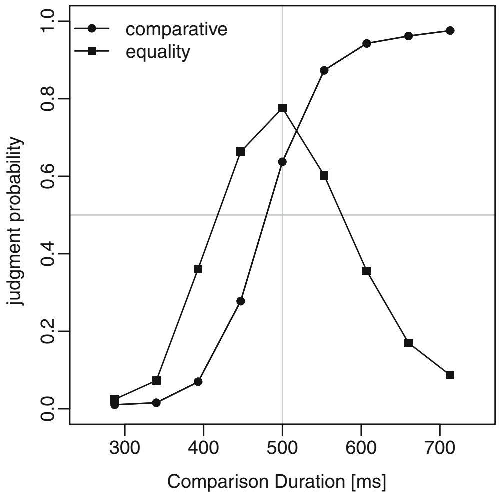

Fig. 7 Relative frequencies of "longer" judgments in the comparative judgment task (circles) and "equal" judgments in the equality judgment task (squares) as a function of oddball duration in Experiment 2. Relative frequencies are collapsed over all participants

Apparatus, stimuli, and procedure

The same experimental setup and procedure were used as in Experiment 1a, with the following exceptions. Two pure sinusoidal tones of 440 and 659 Hz (musical A4 and E5 or a′ and e″, respectively) served as stimuli. They were presented binaurally via stereo headphones (SONY MDR-XD 200) at an intensity of approximately 63 dB(A) SPL as measured at the participant's ears. The standard duration and the comparison durations were the same as in Experiments 1a and 1b, including 5-ms rise and fall times to avoid clicking noises. During the presentation of the stream of auditory stimuli, a steady white fixation cross was presented in the middle of the screen that was replaced by the aforementioned question mark when a response was required. Figure 6 illustrates the trial structure.

Design, dependent variables, and analysis

Details were equivalent to Experiment 1a. The assignment of the two tones to the "oddball" and "standard" conditions were again counterbalanced across participants, as were the possible key assignments.

Results and discussion

The relative frequencies of "longer" and "equal" judgments, averaged across all participants, are shown in Fig. 7. Overall, participants responded "longer" on 52.9 % of the comparative judgment trials and "equal" on 34.6 % of the equality judgment trials.

The mean CE in the comparative judgment task was −12 ms, which was indicative of a significant OE, $t(31) = 2.19$, $p = .036$. The mean CE in the equality judgment condition was 6 ms, which did not differ significantly from zero, $t(31) = 1.25$, $p = .222$, but was numerically indicative of an underestimation of odd stimuli rather than of an overestimation.[2]

One-factorial ANOVAs were conducted as before to investigate possible effects of oddball position (see Fig. 8). In the comparative judgment task, a main effect of oddball position was present, $F(2,62) = 6.99$, $MSE = 297$, $p = .002$, indicating that oddball position modulated the overestimation of the oddball stimuli. Post hoc Tukey's HSD tests uncovered again significant differences in CE between early ($M = -3$ ms, $SD = 34$ ms) and middle ($M = -19$ ms, $SD = 33$ ms) oddball positions, and between early and late ($M = -13$ ms, $SD = 32$ ms) oddball positions, both at a $p < .05$ significance level. CEs did not differ significantly for middle and late oddball positions. As in Experiment 1a, no effect of oddball position was found on CE for the equality judgment task, $F(2,62) = 1.14$, $MSE = 225$, $p = .327$.

Experiment 2 did not entirely replicate the results of Experiment 1a. Even though the OE was still present in the comparative judgment task, it disappeared in the equality judgment task. The result pattern of Experiment 2 corresponds to those reported by Schneider and Komlos (2008) and Valsecchi et al. (2010).

General discussion

The purpose of this study was to investigate the role of decision processes in the duration perception of oddball stimuli. Therefore, we examined whether the OE could also be observed when participants perform an equality judgment task rather than the commonly used comparative judgment task. Former research results suggest that these two tasks access different processes (Schneider & Komlos, 2008; Valsecchi et al., 2010). Accordingly, comparative judgments tend to be influenced by decision biases, whereas equality judgments should not. Both judgment tasks were employed in a visual oddball paradigm manipulating the task either within (Experiment 1a) or between (Experiment 1b) subjects and in an auditory oddball paradigm (Experiment 2, within-subjects manipulation of task).

[2] It is unlikely that this null effect reflects a lack of statistical power. A power analysis revealed that with an assumed alpha level of .05, an OE of 30 ms (resembling the OE observed in the equality judgment data of Experiment 1a), and a sampling variability of 781 ms (resembling the standard deviation of the constant errors observed in Experiment 2, which was larger than that observed in Experiment 1a), the statistical power of obtaining a significant result is larger than 99 %. Even a smaller assumed OE—for example, only 15 ms—would still be detected with a power of larger than 90 %.

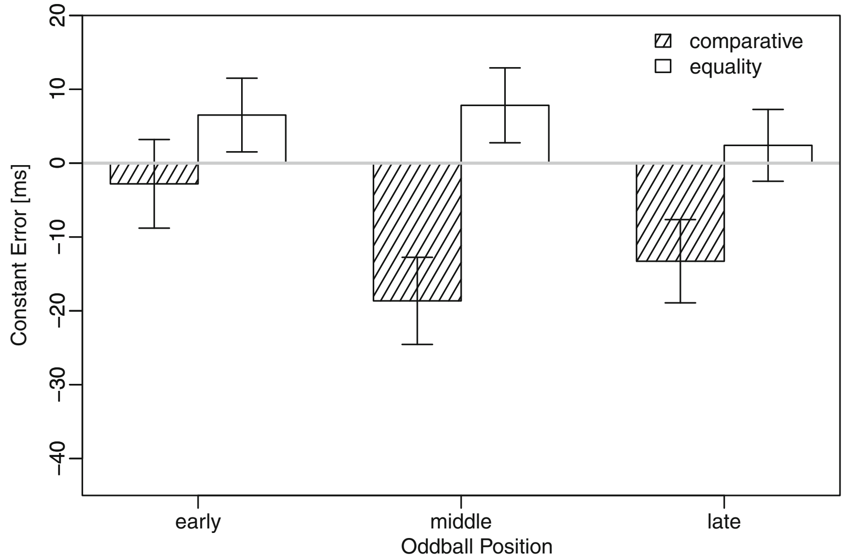

Fig. 8 Mean auditory constant errors (CEs; CE = PSE – standard) separately for early, middle, and late oddball positions in the stream. Striped bars represent the comparative judgment task, and plain bars the equality judgment task in Experiment 2. Error bars represent ±1 standard error

An OE was present in both judgment tasks in the visual oddball paradigm (Experiments 1a and 1b). Hence, these results are consistent with the idea that the OE is of perceptual origin in the visual modality. Furthermore, this pattern of results was observed irrespective of whether the tasks were manipulated within (Experiment 1a) or between (Experiment 1b) subjects. Thus, there was no evidence of carryover influences causing the judgment-independent OE when participants performed the two tasks in alternating blocks of trials. Partly different results were observed in the auditory oddball paradigm (Experiment 2). Here, an OE occurred in the comparative but not in the equality judgment task. This pattern of results is in line with those reported by Schneider and Komlos (2008) and Valsecchi et al. (2010) and could suggest an involvement of decision processes in the emergence of the OE in the auditory modality. As was discussed above, Schneider and Komlos argued that the equality judgment data reveal veridical perception, whereas the comparative judgment data may be biased by decisional processes. Hence, according to these authors' reasoning, the results of Experiment 2 could be attributed to a decisional bias causing the overestimation of oddballs in the comparative judgment task. If one proceeds strictly from the logic of Schneider and Komlos, one has to conclude that the OE originates from a perceptual level for visual stimuli but is due to a decision bias for auditory stimuli. Even though this would explain the complete pattern of the present results, this conclusion appears to be neither plausible nor parsimonious. As will be shown below, it is possible to account for the complete result pattern by an elaborated version of their model.

According to the original model by Schneider and Komlos (2008), participants base their judgments in both tasks (i.e., comparative and equality judgment task) on the subjective difference $\mathbf{\Delta} = \mathbf{C} - \mathbf{S}$, where $\mathbf{S}$ is the internal representation of the standard and $\mathbf{C}$ is the internal representation of the variable comparison stimulus—that is, the oddball. Note that on each trial, participants encounter multiple presentations of the standard stimulus. This possibly influences the buildup of the internal representation $\mathbf{S}$. Since we are primarily concerned with how the representation of the oddball is compared with the representation of the standards, we focused our modeling on this comparison process, rather than on the buildup of the internal representations (see Dyjas, Bausenhart, & Ulrich, 2012, for possible mechanisms). In the comparative judgment task, participants judge the oddball stimulus as being longer than the standard stimulus if the event $\{\mathbf{\Delta} > 0\}$ pertains. In the equality judgment task, an "equal" judgment is associated with the event $\{-\gamma_1 < \mathbf{\Delta} < \gamma_2\}$, where $\gamma_1 > 0$ and $\gamma_2 > 0$ denote the decision criteria, which are assumed to be symmetrical (i.e., $\gamma_1 = \gamma_2$). Under this assumption, symmetrical response functions would emerge, which is also what Schneider and Komlos have observed for contrast discrimination.

Since our psychometric functions are obviously skewed, one might question whether the assumption of symmetrical response criteria is justified. We therefore incorporated two crucial extensions to their original model. First, we allow for asymmetrical response criteria; that is, the size of $\gamma_1 > 0$ and $\gamma_2 > 0$ may differ. Second, we assume that the standard deviation of $\mathbf{\Delta}$ is proportional to the magnitude of the comparison, according to Weber's law. Killeen, Fetterman, and Bizo (1997) have shown that the latter assumption can account for skewed psychometric functions (see also Grondin, 2001a). Furthermore, this model assumes a perceptual OE that is identical for the two judgment tasks as suggested by the results of Experiments 1a and b. In Appendix 1, we show how these assumptions can be incorporated into the model by Schneider

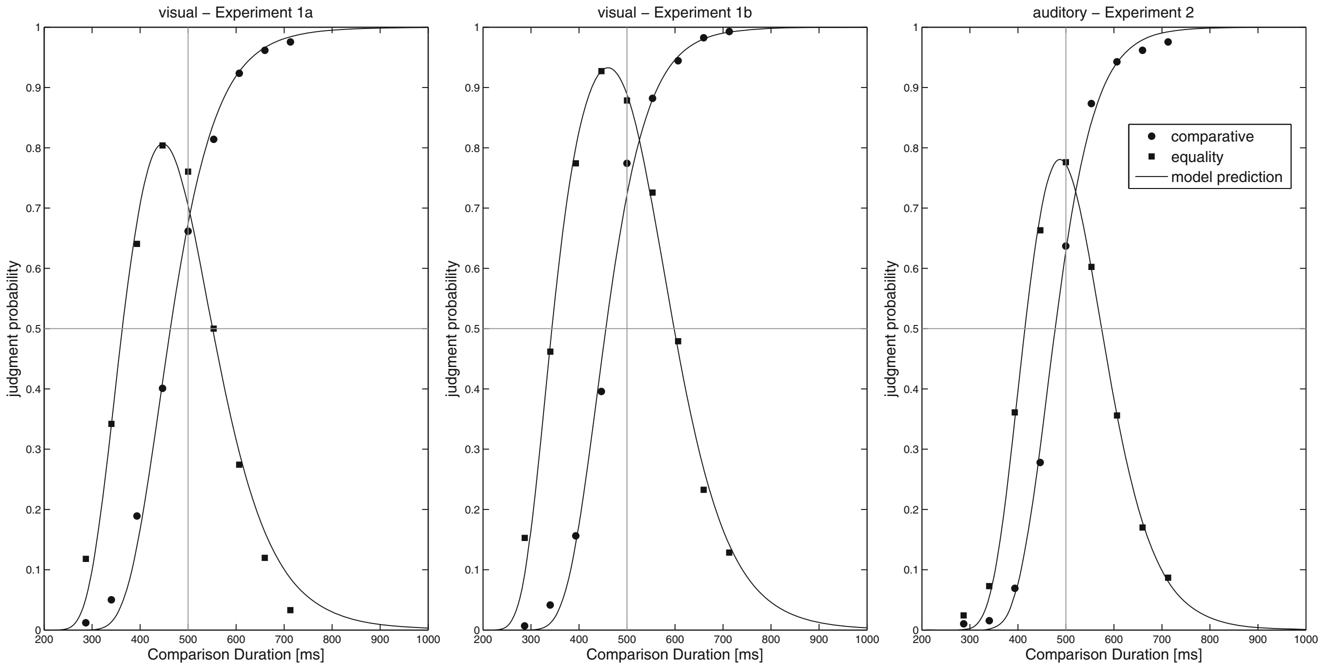

Fig. 9 Model fits for both judgment tasks of Experiment 1a (left), Experiment 1b (middle), and Experiment 2 (right). These figures represent both the original and the elaborated models, since they can be uniquely transformed into each other. The circles represent the observed relative frequencies of "longer" judgments, and the squares the relative frequencies of "equal" judgments as a function of oddball duration. The solid lines depict the model predictions for both judgment tasks

and Komlos (2008). For each of the two experiments, we fitted this elaborated model simultaneously to both judgment tasks. The parameters of this model are the Weber fraction k, the two response criteria γ_1 and γ_2, and the effect parameter ε, which represents the size of the OE. The parameters k and ε were determined to be identical for the two judgment tasks (all parameters were simultaneously fitted to both judgment tasks). Therefore, a total of four parameters had to be estimated for each experiment. A numerical procedure (fminsearch in MATLAB®; Lagarias, Reeds, Wright, & Wright, 1998) was employed to minimize the mean squared error (MSE).

The resulting model fits are depicted in Fig. 9 for the three experiments. As can be seen, the elaborated model nicely captures the observed data pattern, including the skewness of the estimated functions. The upper part of Table 1 contains the estimated parameters. The estimates for k are reasonable, and they also show the common finding that the Weber fraction is larger for visual than for auditory stimuli (e.g., Penney, Gibbon, & Meck, 2000). Consistent with the majority of previous temporal oddball studies, the effect parameter ε reveals a typical OE, which is somewhat larger for the visual than for the auditory modality. Within the elaborated model, response criteria are allowed to vary independently. The parameter values of γ_1 and γ_2 did attain dissimilar values, especially in Experiment 2, in order to achieve an optimal fit within this model. The estimated value 22 ms of ε in Experiment 2

Table 1 Estimated parameters of the elaborated and the original model for Experiment 1a, 1b (visual stimuli), and Experiment 2 (auditory stimuli)

	Estimated Parameters				
Elaborated model	$\hat{\varepsilon}$	$\hat{\gamma}_1$	$\hat{\gamma}_2$	$\hat{k}$	MSE
Experiment 1a	37	−100	92	0.16	0.02
Experiment 1b	44	−112	143	0.15	0.01
Experiment 2	22	−63	101	0.14	0.01
	Estimated Parameters				
Original model	$\hat{\varepsilon}_c$	$\hat{\varepsilon}_e$	$\hat{\gamma}$	$\hat{k}$	MSE
Experiment 1a	37	41	96	0.16	0.02
Experiment 1b	44	29	128	0.15	0.01
Experiment 2	22	4	82	0.14	0.01

Note. The unit of the estimates $\hat{\varepsilon}$, $\hat{\gamma}$, $\hat{\gamma}_1$, $\hat{\gamma}_2$ is milliseconds.

represents a latent OE that applies to both judgment tasks. Consequently, asymmetrical response criteria in the equality judgment task could conceal a true OE in this task.

We also fitted the original version of the model from Schneider and Komlos (2008) to the present data. As was outlined above, this version assumes symmetrical response criteria for the equality judgment ($\gamma = \gamma_1 = \gamma_2$). In order to allow for different sizes of the OE, individual effect parameters were associated with the two judgment tasks (i.e., ε_c and ε_e for comparative and equality judgments, respectively; within the framework of the original model, ε_c is assumed to represent a response bias). The standard deviation of $\mathbf{\Delta}$, however, was again assumed to be proportional to the comparison duration to account for the skewed psychometric functions. This version also involves four free parameters (ε_c, ε_e, k, and γ). The estimated parameters for this model are contained in the lower part of Table 1. As can be seen, reasonable parameter estimates also emerged for this model version. As compared with Experiments 1a and b, the OE is generally smaller in Experiment 2 and almost disappears for the equality judgment.

When comparing the predictions of the two model versions, several points can be noted. First, the goodness of fits of the two models are identical; that is, the two models cannot be distinguished empirically (see also Fig. 9). In fact, it can be shown formally that the two models mimic each other, due to a trade-off between the effect parameter of the equality judgment and its criteria parameters (Appendix 2). Second, the two models predict the same size of OE for the comparative judgment task. Third, the estimated Weber fractions do not differ between the two models. Finally and most crucially, the estimated OE for the equality judgment depends on the assumption concerning the response criteria. A latent OE in the equality judgments could be present or not, depending on whether one proceeds from asymmetrical or symmetrical response criteria, respectively. Therefore, the results of the equality judgments are ambiguous with respect to the nature of the OE. In other words, the absence of an OE in the equality judgment need not indicate a decision bias in the comparative judgment.

The idea that the OE observed in the comparative judgments has a perceptual origin is strengthened by the finding that the OE increased with oddball position, at least for Experiments 1a and 2. As was mentioned in the introduction, such a modulation of the OE can be easily explained by perceptual accounts such as repetition suppression (Eagleman & Pariyadath, 2009; Matthews, 2011; Pariyadath & Eagleman, 2012) or an earlier timing onset of oddballs at later positions due to better temporal preparation (Kim & McAuley, 2013). This result is hardly compatible with the view that the OE is the sign of a decision bias.

Although the OE increases with oddball position, this effect may not be attributed to the stimulus' "oddness" or novelty per se. In the present oddball paradigm, novelty is inevitably confounded with the oddball's position. Therefore, the perceived duration of any stimulus presented late in the stream could principally be overestimated, regardless of whether this stimulus is odd or not. Importantly, however, an OE has also been reported by studies presenting only one standard and one oddball per trial (i.e., reminder tasks; see Matthews, 2011; Ulrich et al., 2006). As such a design prevents possible influences of position, position effects cannot solely account for the occurrence of the OE. Nevertheless, future research on the OE should use and possibly combine various paradigms in order to disentangle the true impact of the concepts oddness, novelty, or violation of expectancy on perceived duration (Pariyadath & Eagleman, 2007).

The present study investigated the OE for both a comparative and an equality judgment task. It has been argued that PSE effects observed in the comparative judgment task could reflect a decision bias rather than a perceptual distortion, whereas the equality judgment task depicts veridical perception (Schneider & Komlos, 2008). The present results, together with the present modeling, do not support this line of reasoning. Specifically, it was demonstrated that the equality judgment cannot distinguish between a latent OE of perceptual origin and a decision bias. Furthermore, modulations of the OE by oddball position point to a perceptual origin of the effect.

Appendixes

Appendix 1

In this Appendix we present an elaboration of the model suggested by Schneider and Komlos (2008). We suggest two modifications of their original model. One crucial assumption concerns the response criteria for the equality judgment. In contrast to the original model, we do not restrict response criteria to be symmetrical. A second modification concerns the variance of the internal representation of the perceived difference between the standard and the comparison durations. The original model assumes that the variance does not change with the magnitude of the stimulus. Here, we assume that this variance increases with stimulus magnitude according to Weber's law. The latter modification accounts for the skewed response functions that are usually observed not only in temporal equality judgment tasks (e.g., Dyjas & Ulrich, 2013; Paul et al., 2011; Wearden, 2003; Wearden & Bray, 2001), but also in comparative judgment tasks (Grondin, 2001a).

Let **S** and **C** represent the internal representations of the standard duration, s, and the variable comparison duration (i.e., the duration of the oddball), c, respectively. **S** and **C** are assumed to be random variables with mean $\mu_s = s$ and $\mu_c = c + \varepsilon$, where ε is the effect parameter. All judgments are based on $\mathbf{\Delta} = \mathbf{C} - \mathbf{S}$. It is convenient to assume that $\mathbf{\Delta}$ follows a normal distribution. The expected value of $\mathbf{\Delta}$ is

$$E(\mathbf{\Delta}) = c + \varepsilon - s. \quad (3)$$

Following Killeen et al. (1997) and consistent with Weber's law, the standard deviation of this difference should be proportional to the size of the comparison stimulus; that is,

$$SD(\mathbf{\Delta}) = k \cdot c \quad (4)$$

where k denotes the Weber fraction. These assumptions underly both the comparative judgment and the equality judgment.

Equality judgment

Let γ_1 and γ_2 denote the response criteria. According to the elaborated model, an equal judgment is elicited if $\gamma_1 < \mathbf{\Delta} < \gamma_2$—that is, when the difference $\mathbf{\Delta}$ lies within the interval $[\gamma_1,\gamma_2]$. The probability of this event occurring is

$$P(\gamma_1 < \mathbf{\Delta} < \gamma_2) = P(\mathbf{\Delta} < \gamma_2) - P(\mathbf{\Delta} < \gamma_1) \quad (5)$$

$$= \Phi\left(\frac{\gamma_2 - (c + \varepsilon - s)}{k \cdot c}\right) - \Phi\left(\frac{\gamma_1 - (c + \varepsilon - s)}{k \cdot c}\right). \quad (6)$$

Comparative judgment

For a comparative judgment, the comparison is judged to be longer than the standard if the internal representation of the oddball duration is larger than that of the standard duration. The probability of this event is

$$P(\mathbf{C} > \mathbf{S}) = P(\mathbf{C} - \mathbf{S} > 0) \quad (7)$$

$$= 1 - P(\mathbf{C} - \mathbf{S} \le 0) \quad (8)$$

$$= 1 - P(\mathbf{\Delta} \le 0) \quad (9)$$

$$= 1 - \Phi\left(\frac{0 - (c + \varepsilon - s)}{k \cdot c}\right) \quad (10)$$

$$= \Phi\left(\frac{c + \varepsilon - s}{k \cdot c}\right). \quad (11)$$

As was mentioned by Killeen et al. (1997), this pseudo-normal model does not resemble the classic Gaussian psychometric function but, rather, is skewed. Furthermore, this model is not a genuine distribution function because it does not approach 1. It must be noted, however, that the deviation from 1 would not be noticeable for realistic values of k. For example, for $k = 0.1$, the asymptotic value is $\Phi\,(10) \approx 1$.

Appendix 2

The purpose of this Appendix is to demonstrate that the original model by Schneider and Komlos (2008) and the elaborated model presented in the main text cannot be distinguished empirically on the basis of equality judgments. The proof presented below is rather general, because it does not require any distributional assumption.

First, consider the original model by Schneider and Komlos (2008). For this model, the probability of an "equal" response for comparison duration c and standard duration s is generally given by $P(-\gamma < \mathbf{\Delta} < \gamma)$. The random variable $\mathbf{\Delta}$ can be written as $\mathbf{\Delta} = \mathbf{E} + c + \varepsilon_e - s$, where $\mathbf{E}$ represents a random variable with the expected value of zero—that is, $E(\mathbf{E}) = 0$. Therefore, the expected value of $\mathbf{\Delta}$ is given by $E(\mathbf{\Delta}) = c - \varepsilon_e + s$. Remember that ε_e is the effect parameter and defines the position of the psychometric function on the c-axis (ε_e reflects the OE for the equality judgment). Consequently, the probability of an "equal" response can be rewritten as,

$$P(-\gamma < \mathbf{\Delta} < \gamma) = P(-\gamma < \mathbf{E} + \varepsilon_e + c - s < \gamma) \quad (12)$$

$$= P(-\gamma - \varepsilon_e < \mathbf{E} + c - s < \gamma - \varepsilon_e) \quad (13)$$

$$= P(a < \mathbf{\Delta} < b). \quad (14)$$

Second, an analogous analysis is applied to the elaborated model. For this model, the probability of an "equal" response is given by $P(\gamma_1 < \mathbf{\Delta}^* < \gamma_2)$. The variable $\mathbf{\Delta}^*$ can be expressed as $\mathbf{\Delta}^* = \mathbf{E} + c + \varepsilon - s$, with $E(\mathbf{E}) = 0$. For the elaborated model, the expected value of $\mathbf{\Delta}^*$ is given by $E(\mathbf{\Delta}^*) = c - \varepsilon + s$. The parameter ε reflects the effect parameter in this model. Thus, we can write the probability of an "equal" response as

$$P(\gamma_1 < \mathbf{\Delta}^* < \gamma_2) = P(\gamma_1 < \mathbf{E} + \varepsilon + c - s < \gamma_2) \quad (15)$$

$$= P(\gamma_1 - \varepsilon < \mathbf{E} + c - s < \gamma_2 - \varepsilon) \quad (16)$$

$$= P(a < \mathbf{\Delta} < b). \quad (17)$$

Consequently, the predicted probabilities embodied in Eqs. 14 and 17 are identical. In fact, the following two identities between the parameters of the two models must hold,

$$-\gamma - \varepsilon_e = \gamma_1 - \varepsilon \tag{18}$$

$$\gamma - \varepsilon_e = \gamma_2 - \varepsilon. \tag{19}$$

As a numerical demonstration, consider the estimated parameter values of Experiment 1a in Table 1—that is, $\widehat{\varepsilon} = 37$, $\widehat{\gamma}_1 = -100$, $\widehat{\gamma}_2 = 92$ (elaborated model) and $\widehat{\varepsilon}_e = 41$, $\widehat{\gamma} = 96$ (original model). Inserting these values into Eqs. 18 and 19 confirms the above identities,

$$-96 - 41 = -100 - 37 = -137 \tag{20}$$

$$96 - 41 = 92 - 37 = 55. \tag{21}$$

The same exercise can be performed for the estimated parameters of Experiments 1b and 2.

Finally, it might be illuminating to note that one cannot discriminate between a zero OE with symmetrical response criteria—that is, $\varepsilon_e = 0$ and $\gamma > 0$ (original model)—and a nonzero OE with asymmetrical response criteria—that is $\varepsilon \neq 0$ and $|\gamma_1| \neq |\gamma_2|$ (elaborated model). For example, consider the original model with $\varepsilon_e = 0$ and $\gamma > 0$—that is, no perceptual OE and symmetrical criteria—and let g be an arbitrary constant ($g \neq 0$),

$$P(-\gamma < \Delta < \gamma) = P(-\gamma + g < \mathbf{\Delta} + g < \gamma + g) \tag{22}$$

$$= P(\gamma_1 < \mathbf{\Delta} + g < \gamma_2). \tag{23}$$

It can be seen that Eq. 23 corresponds to the elaborated model with $\varepsilon = g \neq 0$. Thus, the two models can be converted into each other by an appropriate reparametrization of the models' parameters. Therefore, the two model versions are not empirically distinguishable.

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