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SHORT REPORT

What's next?: Time is subjectively dilated not only for 'oddball' events, but also for events immediately after oddballs

Joan Danielle K. Ongchoco[1,2] · Kimberly W. Wong[1] · Brian J. Scholl[1]

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Abstract

Our experience of time is strikingly plastic: Depending on contextual factors, the same objective duration can seem to fly by or drag on. Perhaps the most direct demonstration of such subjective time dilation is the *oddball effect*: when seeing identical objects appear one after another, followed by an "oddball" (e.g., a disc that suddenly grows in size, in a sequence of otherwise static discs), observers experience this oddball as having lasted longer than its nonoddball counterparts. Despite extensive work on this phenomenon, a surprisingly foundational question remains unasked: What actually gets dilated? Beyond the oddball, are the objects just before (or just after) the oddball also dilated? As in previous studies, observers viewed sequences of colored discs, one of which could be the oddball—and subsequently reproduced the oddball's duration. Unlike previous studies, however, there were also critical trials in which observers instead reproduced the duration of the disc immediately before or after the oddball. A clear pattern emerged: oddball-induced time dilation extended to the post-oddball disc, but not the pre-oddball disc. Whence this temporal asymmetry? We suggest that an oddball's sudden appearance may induce uncertainty about what will happen next, heightening attention until after the uncertainty is resolved.

Keywords Time perception · Time dilation · Oddball effect · Attention

Introduction

We use external clocks to stay in sync with the rest of the world, and this is helpful in part because our *internal* clocks so often fail to track reality. In particular, the same objective duration may subjectively feel much longer or shorter depending on many extrinsic contextual factors (e.g., Eagleman, 2008; Grondin, 2010; Matthews & Meck, 2014). For example, time seems to dilate (with durations seeming longer) when stimuli are more complex (e.g., Block, 1978), are less predictable (e.g., Pariyadath & Eagleman, 2008), or contain more discrete events (e.g., Liverence & Scholl, 2012)—or even just when people are focusing on the passage of time in the first place (e.g., Macar et al., 1994).

One of the most pervasive and reliable influences on the subjective passage of time is attention: Spans of time appear dilated when attention is captured or sustained (e.g., Block & Gruber, 2014; Tse et al., 2004). This can contribute to extreme examples of time dilation in rare real-world situations, as when time slows down dramatically in the midst of a life-threatening emergency (such as a car accident) that may demand exceptional focus (e.g., Noyes & Kletti, 1976). But this influence of attention can also be appreciated even in a pedestrian laboratory context, in displays of simple objects. Surely the best and most powerful example of this is the *oddball effect*: in a sequence of otherwise-similar objects (presented one at a time), an 'oddball' (e.g., a disc that grows in size over time, in a sequence of static discs) appears to last longer (e.g., Tse et al., 2004). This phenomenon may be adaptive for the same underlying reason that we shift attention spatially: just as some locations (in space) merit more processing than others, so too do some moments (in time) merit more processing than others. And as a result, attended objects may not only appear bigger or brighter (in space; e.g., Carrasco & Barbot, 2019), but they may also be processed with greater temporal resolution (e.g., Correa et al., 2006; Montagna & Carrasco, 2006).

The oddball effect has been frequently replicated and extensively studied (e.g., Birngruber et al., 2014a, b, 2015; McAuley

✉ Joan Danielle K. Ongchoco
joan.ongchoco@gmail.com

✉ Brian J. Scholl
brian.scholl@yale.edu

[1] Department of Psychology, Yale University, Box 208205, New Haven, CT 06520-8205, USA

[2] Humboldt University of Berlin, Berlin, Germany

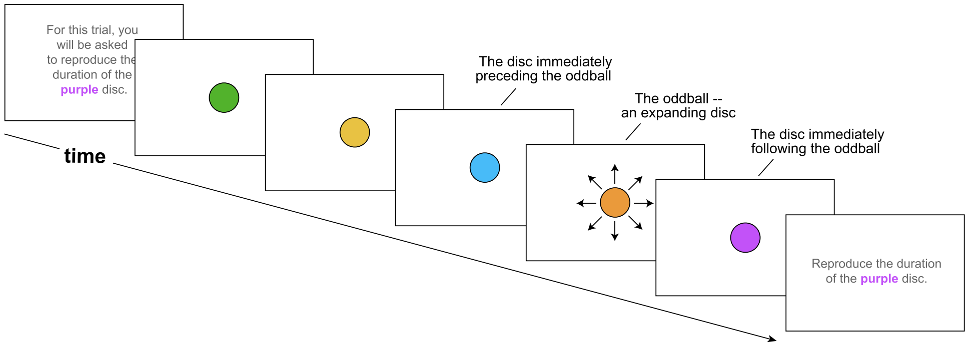

Fig. 1 Caricature of a single Oddball trial in Experiment 1. In this example, the observer reproduced the duration of the postoddball disc, but on other Oddball trials they reproduced the duration of either the pre-oddball disc or the oddball disc itself. (Color figure online)

& Fromboluti, 2014; New & Scholl, 2009; Schindel et al., 2011; van Wassenhove et al., 2008; Wehrman et al., 2020; Wutz et al., 2015). However, to our knowledge, in all past work the only object whose subjective duration was ever queried (when an oddball was present) was the oddball itself. This may obscure what should be a foundational question: What actually gets dilated? Beyond the oddball, are the objects that are presented just before (or just after) the oddball also dilated? If the adaptive benefit of the oddball effect is to draw attention to the unique event itself, then it might seem maladaptive to have the resulting dilation effectively 'leak' into other temporally adjacent events. But if the oddball effect is orienting attention as a function of *uncertainty*, then the resulting dilation may persist (even across subsequent nonoddball objects) until that uncertainty is resolved (where the relevant notion of uncertainty here pertains to the oddball's oddity relative to the other objects in the sequence, and not to the oddball's occurrence throughout the experiment more generally).

Whereas previous work has perhaps most often presented identical stimuli in identical standard durations, we adapted an oddball reproduction task with variable durations and stimuli (e.g., Birngruber et al., 2015; Tse et al., 2004; Wutz et al., 2015)—as depicted in Fig. 1. Observers viewed a sequence of 5 differently colored static discs (so that we could prompt exactly which disc's duration they had to reproduce), each for a different random duration (so that we could prevent entrainment to any particular duration). Then, on half of the trials, one of the discs could be an oddball: it expanded continuously while it was present on the display (from the size of the other discs to a much larger size). The trials came in matched pairs (presented in a globally randomized order), where each sequence of random durations was repeated twice—once with the oddball, and once without. After each sequence, observers reproduced the duration of one of the discs, as indexed by its color in instructions before the trial began (e.g., "Reproduce the duration of the purple disc"). The disc that observers reproduced was always either (a) the oddball, (b) the disc just before the oddball, or (c) the disc just after the oddball. This decouples the oddball from the reproduction itself, such that the oddball is no longer the only task-relevant relevant stimulus—and it thus allows us to compare people's subjective experiences of the other stimuli in the sequence, beyond the oddball. We then directly compared the reproduced durations for matched pairs of trials (for each of these three types) that did or did not have an oddball present.

Experiment 1

Following previous oddball experiments closely (e.g., Tse et al., 2004), we had observers watch discs appear one after another (each for a randomly determined duration), and they simply reproduced the duration of either the third, fourth, or the fifth disc (indexed by its color). Half of the time, the fourth disc of the sequence could be an 'oddball.'

Method

Participants Fifty observers (based in the United States) participated using the Prolific online platform (see Palan & Schitter, 2018) for monetary compensation. This sample size was determined before data collection began, was preregistered, and was fixed to be identical across the experiments reported here. All experimental methods and procedures were approved by the Yale University Institutional Review Board, and all observers confirmed that they had read and understood a consent form outlining their risks, benefits, compensation, and confidentiality, and that they agreed to participate in the experiment.

Apparatus After agreeing to participate, observers were redirected to a website where stimulus presentation and data collection were controlled via custom software written using a combination of HTML, CSS, JavaScript, PHP, Snap.svg, and the JsPsych libraries (de Leeuw et al., 2023). Observers completed the experiment on either a laptop or desktop computer, and observers who attempted to complete the experiment on a phone or tablet were not allowed to continue. (Since the experiment was rendered on observers' own web browsers, viewing distance, screen size, and display resolutions could vary dramatically, and so we report stimulus dimensions below using pixel [px] values.)

Stimuli All text, across the instructions and prompts, was presented in the standard jsPsych CSS style, in the font size of 18 px on a white background. Each colored disc had an initial diameter of 100 px, with a black 5-px outline. Discs could be blue (#48BBF8), green (#52B22C), orange (#EA9A3B), purple (#C252F8), and yellow (#E8C243); see Fig. 1. Oddball discs grew to four times their original diameter over the course of their full durations.

Procedure and design At the beginning of the experiment, observers were shown all five colored discs and were told that they would be required to distinguish between the different colors. For each trial, observers were first told the color of the specific disc whose duration they would have to reproduce. This target disc always appeared at either position 3, 4, or 5 of the 5-disc sequence. To begin the trial, observers pressed a key. The sequence began with a fixation cross (60 px), the duration of which was randomly sampled between 500 ms, 750 ms, and 1,000 ms. Five discs then appeared one after another at the center of the display (with the color order randomized on each trial). The duration of each disc was randomly sampled between 1,000 ms and 2,000 ms, and discs were interleaved with blank intervals, whose durations were also randomly sampled between 1,000 ms and 2,000 ms. On each trial, the fourth disc in the sequence could either expand (in the Oddball condition) or not (in the No-Oddball condition). The specific durations of both each disc and each blank interval that were randomly determined for every given Oddball trial were then repeated exactly in a corresponding No-Oddball trial (which appeared in a different random trial in the experiment), to facilitate a comparison between these conditions. As a result, all display durations for Oddball and No-Oddball trials were perfectly matched across conditions. After all discs had been presented, observers reproduced the duration of the target disc by holding down a key. Figure 1 depicts a caricature of an Oddball trial.

Each observer first completed a single practice trial during the instructions, and then completed (in a random order, randomized differently for each observer) 36 trials: 2 sequence types (Oddball vs. No Oddball) $\times$ 3 possible target positions (3, 4, 5) $\times$ 6 repetitions (each with a different set of random disc durations)—with an additional 4 'attention-check' trials (where observers were asked what was the color of the target disc). At the one-third and two-thirds marks, observers were given a self-timed break.

Preregistered exclusion criteria After the experiment, observers completed a debriefing questionnaire where they were asked how well they paid attention (on a continuous scale, with 1 being very distracted and 100 being very focused). Observers who reported an attention level below 75 were excluded without ever recording their data ($n = 5$). We also excluded observers whose average performance in the attention-check trials was below 75% ($n = 6$), observers whose mean reproduction duration was greater than 2 standard deviations below the mean reproduction duration of all observers ($n = 3$), and observers whose standard deviation across reproduction durations was less than 100 ms ($n = 3$). We also implemented three trial-level exclusions: (1) individual trials whose reproduced duration was 2 standard deviations away from that observer's mean reproduced duration ($M = 1.45$, $SD = 0.94$; and we then computed the grand mean reproduction duration after this); (2) any other individual trials whose reproduction durations were 100 ms or less ($M = 0$, $SD = 0$); and (3) any other individual trials whose reproduction durations were greater than or equal to 2 standard deviations above the grand population mean ($M = 1.14$, $SD = 2.10$).

Results

As a measure of subjective time dilation, each reproduced duration was first normalized by dividing it by the corresponding actual duration. Oddball effects were then quantified by further dividing this normalized duration for each Oddball trial by the normalized duration for its corresponding No-Oddball trial (where 'corresponding' here just refers to the use of matched disc durations and the same probed disc). Resulting values greater than 1 thus indicated subjective oddball-induced time dilation (while values less than 1 would indicate subjective oddball-induced time contraction).[1] These values (and their means) are depicted in Fig. 2a for the Pre-Oddball, Oddball, and Post-Oddball trials. Inspection of this figure reveals a clear pattern: there was reliable subjective oddball-induced time dilation not only for the oddball disc itself, but also for the post-oddball disc—but not for the pre-oddball disc. These impressions were verified by the following analyses: the Oddball/No-Oddball ratios of normalized reproduced durations were significantly greater than 1 for the Oddball disc ($M = 1.12$, $SD = 0.21$), $t(49) = 3.92$, $p < 0.001$, $d = 0.55$, and for Post-Oddball disc ($M = 1.11$, $SD = 0.31$), $t(49) = 2.55$, $p = 0.014$, $d = 0.36$, but not for the Pre-Oddball

[1] Dividing corresponding Oddball and No-Oddball trials in this way effectively isolates that difference in reproduction that is due solely to the Oddball (since the corresponding trials share identical timings and reproduced disc position). This therefore factors out alternative potential influences that could affect attention (besides the Oddball being present), such as the "foreperiod" or "hazard" effect (wherein attention may gradually heighten as the sequence progresses before an oddball appears; e.g., Wehrman et al., 2020).

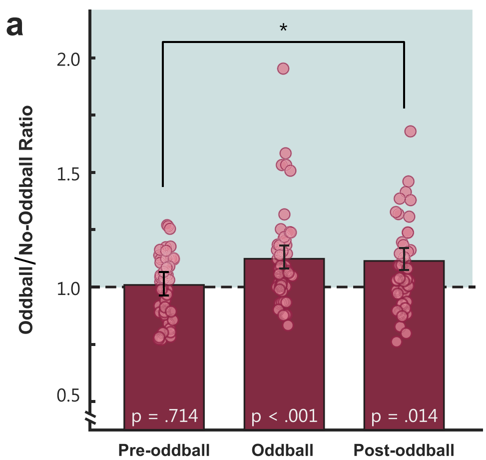

Fig. 2 Results from **a** Experiment 1 and **b** Experiment 2, depicting the normalized reproduction duration for each Oddball trial divided by the normalized reproduction duration for its corresponding No-Oddball trial for each disc position (see the main text for details). Error bars reflect 95% confidence intervals. Dashed lines mark the ratio that indicates no subjective temporal distortion (1.0), where values greater than 1 (shaded green) indicate subjective time dilation. Single asterisk represents $p < .05$ (Color figure online)

disc ($M = 1.01$, $SD = 0.14$), $t(49) = 0.37$, $p = 0.714$, $d = 0.05$—with a reliable interaction between the two non-oddball discs, $t(49) = 2.04$, $p = 0.047$, $d = 0.29$.

Experiment 2

In Experiment 1, the oddball disc only ever appeared in sequence position 4, and observers were only asked to reproduce the durations of discs in positions 3, 4, or 5—such that the Post-Oddball disc was also always the final disc in the sequence, which may be evocative of recency or final-item effects. To ensure that the discovery of time dilation for the Post-Oddball disc was due to its position relative to the Oddball (and not to its position relative to the end of the sequence, as only or always the last item), we replicated Experiment 1 (again with 5-disc sequences), but now the Oddball was only ever presented in position 3, such that the Post-Oddball disc was the penultimate disc in the sequence.

Method

This experiment was identical to Experiment 1, except as noted. A unique set of 50 observers were recruited through Prolific. The pool of potential target discs was shifted one disc earlier, such that the target disc (whose duration needed to be reproduced) in each trial could be at either position 2, 3, or 4 of the 5-disc sequence, and the third disc (instead of the fourth) was the designated oddball disc that could expand in size in the Oddball trials.

We again excluded observers who reported an attention level below 75 ($n = 11$), whose average performance in the attention-check trials was below 75% ($n = 3$), whose mean reproduction duration was greater than 2 standard deviations below the mean reproduction duration of all observers ($n = 0$), and whose standard deviation across reproduction durations was less than 100 ms ($n = 2$). And we excluded individual trials according to the same three preregistered criteria—respectively excluding (1) $M = 1.59$, $SD = 0.98$, (2) $M = 0.27$, $SD = 1.59$, and (3) $M = 0.67$, $SD = 4.76$.

Results

These values (and their means) are depicted in Fig. 2b for the Pre-Oddball, Oddball, and Post-Oddball trials. Inspection of this figure reveals the same pattern of results observed in Experiment 1. The Oddball/No-Oddball ratios of normalized reproduced durations were again significantly greater than 1 for the Oddball disc ($M = 1.21$, $SD = 0.20$), $t(49) = 7.42$, $p < 0.001$, $d = 1.05$, and for the Post-Oddball disc ($M = 1.11$, $SD = 0.24$), $t(49) = 3.05$, $p = 0.004$, $d = 0.43$, but not for the Pre-Oddball disc ($M = 1.02$, $SD = 0.17$), $t(49) = 0.87$, $p = 0.387$, $d = 0.12$—again with a reliable interaction between the two non-oddball discs, $t(49) = 2.09$, $p = 0.042$, $d = 0.30$.

General discussion

Empirically, the core result of the present study was the discovery that oddball-induced time dilation applies not only to the oddball itself, but also to the object immediately following the oddball (but not to the object immediately preceding the oddball). Despite the popularity of the oddball effect, previous studies could not have observed this current result, because they never tested for the subjective duration of any of the non-oddball objects in a sequence with the oddball present. (Indeed, the only study we know of that tested for oddball-induced time dilation for objects other than the oddball did so not for other objects in the sequence, but for objects in other spatial regions of the display; New & Scholl, 2009).

Theoretically, this result changes our understanding of what actually gets dilated by oddballs—and this may even require a change in how the oddball effect is characterized in the first place. While different theoretical accounts and underlying mechanisms have been proposed for the oddball effect (e.g., Cai et al., 2015; Eagleman & Pariyadath, 2009; Matthews et al., 2014), these accounts have all focused on observers' experiences *of the oddball itself*. And in fact, previous work has often simply defined the "oddball effect" not only in terms of the oddball as the *cause* of the dilation, but also of the oddball as the (sole) *target* of the dilation. For example:

- "The temporal oddball effect … describes the finding that rare, deviant stimuli (oddballs) are temporally overestimated as compared to standards of equal physical duration." (Birngruber et al., 2014b)
- "[I]f a single presentation of an oddball stimulus … is presented within a train of repeated presentations of a standard stimulus …, then the oddball can seem to persist for longer than the repeated presentations of the standard stimulus.… We will refer to this as the oddball effect." (Schindel et al., 2011)
- "[We] use a well-established oddball paradigm, in which individuals are typically asked to judge the duration of a deviant (oddball) stimulus embedded within a rhythmic sequence of otherwise identical stimuli." (McAuley & Fromboluti, 2014)

Based on the results from the current study, none of these definitions seems quite right (and similar descriptions can also be found in book chapters and review articles; e.g., Eagleman, 2008; Matthews & Meck, 2016; Phillips, 2013; Tse, 2010; Ulrich & Bausenhart, 2019): instead, the oddball effect involves subjective time dilation *due to* the salience or unexpectedness of the oddball, for *both* the oddball and (at least) the object immediately following the oddball.

Why does the oddball effect apply even to the post-oddball object? And why does it *not* apply to the pre-oddball object as well? Part of the answer may simply be that the oddball object and the post-oddball object are unique insofar as they are the only two objects in the sequence that are not identical to the immediately preceding object. (The oddball is odd relative to the preceding objects in the sequence, but the post-oddball object is also odd relative to the just-disappeared oddball itself—even though it simply returns to the preceding pre-oddball pattern.) This would be consistent with previous work in which the second of two images is experienced as lasting longer when it is novel rather than repeated (Matthews, 2011). Moreover, when interpreting these results in the context of the broader time perception literature, they are also consistent with the possibility that the oddball may have increased the pulse rate of our "internal pacemaker" (e.g., Wearden, 2016), and it might then simply take time for the pulse rate to come back to baseline (a natural idea, but one never explored in this empirical context).

In addition, however, we speculate that the current results may reflect the adaptive role of the oddball effect in the first place. In particular, the oddball effect may arise due to the introduction (by the oddball) of *uncertainty* about what will come next. On the scale of the full experiment, what might come next may seem trivial—since no discs ever expanded after an oddball appeared. But on a local level, in each individual sequence, a deviant stimulus may nevertheless still trigger a reset in the visual system, regardless of what subjects may be consciously expecting (in a manner similar to work on attentional capture by properties such as sudden onset; e.g., Egeth & Yantis, 1997). Previous work has suggested that uncertainty can incite arousal and capture attention (e.g., Eagleman, 2008; Mathys et al., 2014; Mathys, 2011; Pariyadath & Eagleman, 2007; Tse et al., 2004; Wehrman et al., 2020)—and this attentional boost may persist until the uncertainty is resolved, which does not occur until *after* the return to 'normalcy' in the sequence. (When the post-oddball object is initially presented, you cannot yet know if it will be odd or not, and so time might continue to be dilated until that is resolved!) In this way, an oddball might orient attention (and thus dilate time) not only for what is currently happening, but also for what is about to unfold next.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.3758/s13414-023-02800-7.

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Open practices The preregistered methods and analyses for both experiments can be viewed at: https://aspredicted.org/blind.php?x=7ga89t (Experiment 1) and https://aspredicted.org/blind.php?x=gk22wi (Experiment 2).

Author contributions J.D.K.O., K.W.W., and B.J.S. designed the research and wrote the manuscript. J.D.K.O. conducted the experiments and analyzed the data with input from K.W.W. and B.J.S.

Data availability All data generated or analyzed during this study are included in this published article (and its Supplementary Information files).

Declarations

Competing interests The authors declare no competing interests.

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