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Eccentricity Advances Arrival to Visual Perception

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We investigated temporal properties of visual perception as a function of eccentricity, that is, spatial position relative to the fovea. Our experiments were motivated by well-characterized non-uniformities in neuron distribution in the human eye and early visual pathways. These non-uniformities have been extensively studied in the context of spatial perception, while largely neglected in relation to temporal perception. In Experiment 1, participants fixated the rapid serial visual presentation letter stream and were instructed to report the letter which appeared simultaneously with a brief cue presented at different locations along the horizontal meridian. Participants exhibited a tendency to report earlier letters with more peripheral as compared to central cues, indicating that they misperceived differently located stimuli as simultaneous even though they were never presented together. Experiment 2 conceptually replicated the findings of Experiment 1. Experiment 3 further demonstrated that the effect is specifically due to eccentricity, and not the relative distance between the stimuli. We argue that such location-based misperceptions of simultaneity arise because transient stimuli at more eccentric locations advance to perception faster than stimuli at or near the fovea. Collectively, these experiments show, for the first time, how processing speed differences across the visual field translate into differences in perceived simultaneity. They also demonstrate, for the first time, location-based misperceptions of simultaneity for stimuli never presented together. Finally, Experiment 4 showed that greater eccentricity also increased the perceived duration of a stimulus compared to fovea. These results reveal the breadth of perceptual effects driven by temporal processing differences across the visual field.

Public Significance Statement

How are events occurring at different times and places integrated into a unified experience of what is happening now? We report experiments that sequester and dissect the visual now, our sense of a present moment in visual experience. In particular, we consider how a moment of visual experience combines events that occur at different times and locations. The results suggest that space and time dissociate as events are stitched into a moment of experience, that a perceived moment can combine stimuli that did not necessarily share an overlapping moment in reality. We explain these results in relation to how neurons in the eye and the brain are distributed to process visual space.

Keywords: eccentricity, time perception, RSVP, temporal expansion, visual present

How does a moment in visual perception combine objects and events from different locations in space? Naïvely, one might assume that if two events take place simultaneously within an observer's field of view, the observer will become aware of those events at the same time. Here, we sought to investigate the possibility that (even neglecting the speed of light) perceived moments may not always correspond to actual moments in terms of their constituent events. One reason to suspect that this may occur is that perceptual experience is the result of a complex processing pipeline in which different features may reach awareness faster than others (Clifford et al., 2003; Moutoussis & Zeki, 1997). Such processing introduces the possibility that two simultaneous but differently located events may not always be perceived simultaneously—and conversely that a perceived moment might present two events as simultaneous despite those events *never* occurring together in the external world. There is also reason to suspect a particular directional hypothesis regarding differently located events. This is because the visual system exhibits significant nonuniformities in neuron distribution in the human eye and early visual pathways. Previous evidence suggests that because information is integrated over fewer neurons in peripheral vision, processing may occur faster in the periphery as compared to the fovea (Carrasco et al., 2003). Given this, we specifically hypothesized that two events might appear as simultaneous even if they were *never* present simultaneously in reality provided that the earlier event occurs at the fovea (where processing is slower) and the later event in the periphery (where processing is faster).

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The reported experiments and results were included in a talk presented during the Annual Meeting of the Vision Sciences Society (2020), viewable here (https://www.youtube.com/watch?v=JQlGu8vNaOw). We have no known conflict of interest to disclose.

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Spatial and Temporal Non-Uniformities Across the Visual Field

Sometimes considered a bug, sometimes a feature (Rosenholtz, 2016), the distribution of photoreceptors in the human retina is radically nonuniform. Cones constitute almost the entirety of the central fovea (Kolb, 2011). And while rods are distributed throughout the retina, their density declines dramatically with increasing eccentricity (distance from the fovea). Whereas the macula (the central portion of the fovea) may contain as many as 150,000 cones per square millimeter, the far temporal periphery may contain as few as 50,000 rods and cones combined per square millimeter (80–90,000 at the edges of the nasal periphery). This pattern is replicated in the receptive fields and concentrations of visual system neurons spatially mapped to external space. As a result, the spatial resolution of human vision is relatively low outside fixated regions of space. The consequences of poor spatial resolution in the periphery have been widely examined in the context of reading (Rayner, 1975; Rayner et al., 2012), visual crowding (see Levi, 2008 for a review; Whitney & Levi, 2011), object tracking (Fehd & Seiffert, 2008, 2010; Upadhyayula & Flombaum, 2020; Zelinsky & Neider, 2008), and change blindness (Henderson & Hollingworth, 2003; T. J. Smith et al., 2012; Zelinsky, 2001).

Less widely considered are the possible temporal implications of these nonuniformities in the eye and the visual system. A relatively small amount of research suggests that temporal resolution is better in the periphery, although the evidence is far less developed than for low spatial resolution. Specifically, peripheral cones are more sensitive to flicker than foveal cones (Himmelberg & Wade, 2019; Sinha et al., 2017), and critical flicker frequency increases with eccentricity (Hartmann et al., 1979; Rovamo & Raninen, 1984).

We were particularly motivated by one seminal study which found faster processing times in the periphery compared to the fovea (Carrasco et al., 2003). The reasoning that motivated this study is that integrating information over fewer neurons should happen more quickly, or to put it more generally, that achieving the high spatial resolution of the fovea takes more time than it takes to achieve the coarse spatial representation of the periphery. A key feature of Carrasco et al.'s study was the use of a signal detection procedure to ensure that the results revealed advantages for speed of processing (in the periphery), not just speed of response. The authors conclude that "the magnitude of the eccentricity effect is likely to have significant perceptual consequences" (Carrasco et al., 2003, p. 700). We sought to investigate one specific potential consequence in the case of simultaneity perception.

Another recent study by Jovanovic and Mamassian (2020a) also investigated temporal processing differences between the periphery and fovea. There, participants were asked to report when a stimulus was presented within a fixed temporal interval. They found that participants reported a stimulus in the periphery sooner than they reported an equivalent stimulus in the fovea. However, to our knowledge, no study has considered the possibility that temporal processing differences across the visual field might result in misperceived relationships between events, specifically illusions of simultaneity: two events seeming to co-occur despite never overlapping in time. We sought to investigate precisely this potential consequence of processing differences across the horizontal meridian.

Illusory Co-Occurrence in Rapid Serial Visual Presentation

To establish whether an observer perceives two items as co-occurring requires a paradigm in which observers report what they see at a given moment. Rapid serial visual presentation (RSVP) is just such a paradigm. In classic experiments, participants watch a stream of letters appear serially at fixation, one letter replacing another in quick succession (e.g., a rate of 200 ms). At some point during the stream, a circle appears surrounding one of the letters, and the task is to report the letter that appears with this cue. Early accounts of performance focused on attentional bottlenecks and manipulations that asked observers to report more than one target over the course of a trial (Chun & Potter, 1995; Raymond et al., 1992). More recent accounts have emphasized probabilistic uncertainty about temporal order: for instance, that observers represent overlapping distributions that describe the order of each letter in the stream (Vul et al., 2009, also see Callahan-Flintoft et al., 2020; Goodbourn et al., 2016; Goodbourn & Holcombe, 2015). Importantly for current purposes, participant responses tend toward normality, centered on the letter that appears together with the cue, with errors extending to preceding and succeeding letters. The paradigm may thus reveal occasions of misperceived simultaneity between a cue and a letter that were never present together.

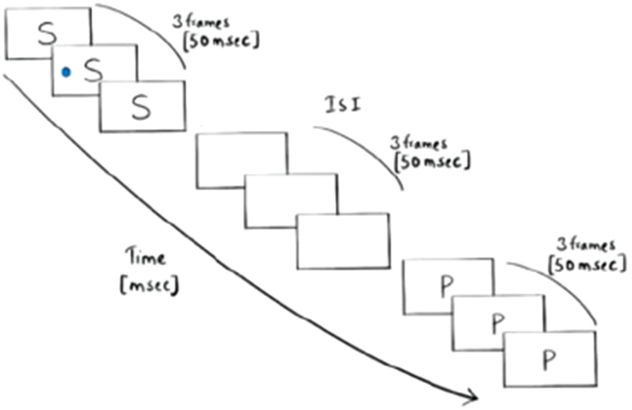
Typical studies rely on cues that circumscribe (and therefore overlap) a target spatially, leaving open the possibility that masking, misbinding, or afterimages, among other factors, could produce misreported detection. Requiring the detection of multiple targets in a stream further complicates the interpretation of past results with respect to perceived simultaneity. We, therefore, adapted a bare-bones version of the RSVP paradigm to address the question of whether and why an observer might misperceive as simultaneous two stimuli that were never present together. Our bare-bones RSVP paradigm was designed to test the specific hypothesis that differences in processing latencies across the horizontal meridian might elicit illusions of simultaneity between peripheral and foveal events which never overlapped in time.

To test this hypothesis, we asked participants to fixate the center of a monitor where RSVP letters appeared. Participants were instructed that at some point during each stream a white disc would appear briefly at a random location along the screen's horizontal meridian. We used a white disc for simplicity and to ensure that the cue could be easily resolved even in the visual periphery. Participants were instructed to report the RSVP letter that occurred with the cue in each trial. We could thereby use fact-of-the-matter serial position errors (SPEs) to evaluate whether participants systematically misperceived simultaneity between peripheral (compared to less peripheral) cues and RSVP stimuli. More generally, we sought to determine whether an observer might occasionally perceive two items as co-occurring when they never overlapped in time.

Experiment 1: Peripheral Stimuli Reach Visual Access More Quickly Than Central Ones

A schematic of the modified RSVP paradigm is shown in Figure 1. As in familiar RSVP tasks, participants were instructed to report the letter that was present when a cue appeared. We manipulated the location of the cue across the visual field to include one eccentric distance and one distance closer to the fixated stream. If

Figure 1
Modified RSVP Task Used in Experiment 1



Note. The task was to report the letter present when the cue appeared (designated as a blue disc in the figure). The cue would always appear for 1 frame in the middle of the 3-frame presentation of one of the letters. See the online article for the color version of this figure.

the visual snapshot of our experience comprises those stimuli which are actually simultaneous in the visual field, then response distributions should on average be centered on accurate simultaneity. Subjects should most often report the letter that actually appeared with the cue, and they should report preceding and succeeding letters equally and less frequently. Any bias in the central tendency of responses would therefore reveal systematically misperceived simultaneity.

Furthermore, if *when* something appears is the sole determinant of when it is perceived—regardless of *where* it appears—then responses to the more central cue should be indistinguishable from responses to the more eccentric cue. However, owing to the putative temporal processing advantage of the periphery over the fovea, we hypothesized that participant reports would reveal a systematic difference between the two cue conditions. Specifically, we hypothesized that peripheral cues would be reported as coinciding with earlier letters as compared to those reported with central cues.

Method

Transparency and Openness Disclosures

The authors designed all the methods and wrote associated code for the experiments reported. Experimental code, analysis scripts, and raw data are made publicly and permanently available through the OSF repository (https://osf.io/q9kun/). All study measures and analyses conducted are reported in the text. There were no participant exclusions. Some sample sizes in the experiments described here were constrained by COVID-19-related circumstances which halted data collection. However, no data were analyzed until the research team agreed that no more data would be collected in each experiment. Analysis plans and methods were not pre-registered, but they closely followed the analyses applied in cited literature with similar methods.

Participants

Thirty-one Johns Hopkins undergraduates participated for course-related credit. We sought to test between 20 and 30 participants based on typical sample sizes for RSVP experiments. The experiment was conducted at the end of a semester, and the stopping protocol was therefore to continue testing until the study pool closed, which produced 31 participants. All participants had normal or corrected-to-normal visual acuity. The study protocol was approved by the Homewood Institutional Review Board (HIRB). Per standard lab practice, all results were immediately deidentified. Demographic data were collected separately and cannot be tracked directly to this or any other experiments in the lab.

Materials

We used an iMac (Retina 5K, Late 2015, Apple Inc, Cupertino, California, USA) and Psychopy3 software to test the participants. Stimuli were presented on a 27-in. display with a refresh rate of 60 Hz (16.667 ms/frame). Participants were seated approximately 55 cm away from the monitor, and the display spanned about 46° × 29°.

Stimuli and Procedure

Participants pressed a key to start each trial, at which point a fixation cross in the center of the display was replaced by the RSVP of each of the 26 letters in the English alphabet (in a random order) against an empty black background. Each letter was presented once for a period lasting three display frames (approximately 50 ms). The interval between letters (ISI) was also three display frames. Letters were printed in white and occupied approximately 2° of visual angle horizontally and vertically (see Figure 1). Participants were instructed to fixate the cross in the center of the display before launching a trial, and they were told to continue fixating the letter stream as it appeared. Fixation was emphasized, but not monitored or enforced.

The task for participants was to fixate the letter stream while also monitoring the horizontal meridian of the display for a cue that would appear once in each trial. At the end of a trial, they were told to report the letter from the RSVP stream which they had perceived at the time when the cue appeared. The cue was always a white disc (approx. 0.5° in radius). It always remained on the screen for only one display frame (i.e., 16.667 ms). In order to impose some unpredictability while allowing for counterbalancing, the cue appeared along with the 6th, 10th, 14th, 18th, or 22nd letter in the RSVP stream of a given trial. It appeared one frame after the given letter onset and then disappeared after the second frame so that the letter remained on the display for one more frame after the cue disappeared. In short, the cue was present for the middle ⅓ of the frames during which the letter was present.

A cue could appear in one of four positions along the display's horizontal meridian, 2° to the left and right of fixation, and 10° to the left and right of fixation. A demonstration of the paradigm can be viewed at (https://youtu.be/6USG9Oyj6hU and https://youtu.be/uc_4h_jE-JU). Each participant completed 120 trials lasting 35–40 min in total.

Results

Participant responses were coded in terms of SPE: the relative forward or backward distance between the letter reported and the correct letter. If the participant responded with a letter that appeared along with the cue, the SPE would be 0, −1 if the reported letter was the one that appeared just before the cue was presented, −2 if the reported letter was two prior, and so on, with positive numbers indicating letters that followed the cue (as opposed to preceding it).

We pooled responses across all participants by visual eccentricity to generate a distribution of SPEs, as shown in Figure 2. We also computed the average SPE for each participant by eccentricity condition.

All statistical analyses were conducted using the Pingouin statistics library in Python (Vallat, 2018). Mauchly's sphericity and Levene's homoscedasticity tests of the data conformed with ANOVA assumptions. A repeated measures ANOVA analysis revealed a significant main effect of the eccentricity condition on the SPEs, $F(1, 30) = 5.545$, $p = .026$, $\eta_{\mathrm{p}}^2 = 0.156$. Further, a post hoc paired t-test analysis revealed a statistically significant difference between the SPE reports for 2° ($M = 0.08$, $SD = 0.32$) and 10° conditions ($M = -0.04$, $SD = 0.38$); $t(30) = 2.35$, $p = .02$ (see Figure 3). Notably, the average SPE for the 10° condition was negative while the average error for the 2° condition was positive. In the 10° condition, participants more frequently reported letters which appeared *before* the cue, while in the 2° condition, they more frequently reported letters that appeared *after* the cue.

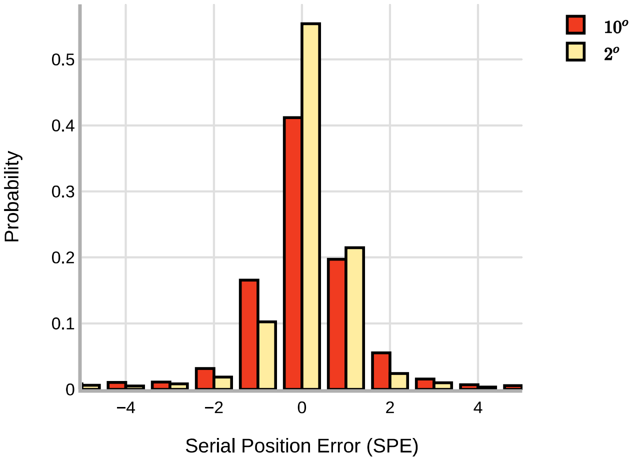
Discussion

Assume that when a stimulus appears on the screen it evokes a sensory response, and that it takes some small amount of time for that evoked response to become an accessible visual impression. If two stimuli are presented at the same exact time—if they simultaneously commence the journey from sensation to perception—then they will become perceived as simultaneous only if they conclude the journey at the same time as well. If they progress at different speeds, however, they may be perceived as having different onsets (and offsets) because they ultimately reach perception separately. Likewise, two stimuli that never co-occurred might still be perceived as simultaneously present, in the event that the stimulus with the later onset progresses faster than the stimulus with the earlier onset—thereby compensating for its late start, so to speak.

In the context of our RSVP experiment, appearing simultaneous with a previous letter from the stream—as opposed to the actual simultaneous letter—means that a cue becomes accessible *faster* than the letters in the stream do. The cue needs to catch up with an already presented letter for them to become perceived together. In Experiment 1, more peripheral cues elicited responses from letters earlier in the stream more frequently than did more central cues. This appeared as more negative SPEs for the more peripheral cues compared to the more central cues. In terms of the temporal processing, these results can be characterized as either an advantage for peripheral processing or a disadvantage for more central processing—because each seems fair descriptively. It is important to note, also, that simultaneity was not always misperceived by participants. The modal response in both cue conditions had an SPE of 0.

Figure 2

Distribution of Responses in Experiment 1



Note. See the online article for the color version of this figure.

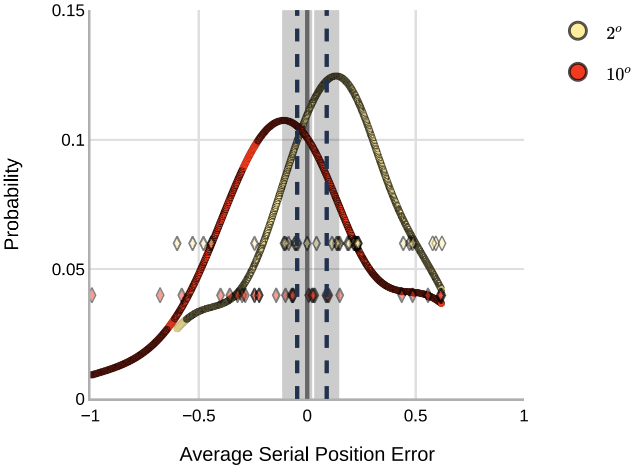
What is key from our perspective is that if one were to subtract average SPEs in the central condition from those in the peripheral conditions, one would be subtracting more positive numbers from more negative ones. Experimentally, reporting letters from the RSVP provides a tool for comparing the relative time to perception for the cues in the two conditions. The inference we can make, therefore, is that (on average and all else being equal) more peripheral cues advance to perception faster than less peripheral cues.

Experiment 2: Conceptual Replication

This experiment was a conceptual replication of Experiment 1 with a slight modification. Cues were presented during the interstimulus interval (ISI) between two RSVP letters, when nothing was present in the location of RSVP. The task for participants was the same: to report the letter that they perceived as simultaneous with the cue. Although there was technically no correct answer, a difference between cue conditions in terms of speed to perception should produce a difference in terms of the tendency to report letters that precede and follow the cues. Given that the cue and the target letter never appeared simultaneously on the screen, the observed tendency in the reports could further reinforce the peripheral versus foveal race to perception, and accordingly the misperceived simultaneity.

Figure 3

Results of Experiment 1



Note. The curves represent the probability density. Each diamond is an individual participant SPE average by condition. Dashed lines show means by conditions, with shade to show the standard error of mean. See the online article for the color version of this figure.

Method

The experiment was identical to Experiment 1, except as follows.

Participants

A total of 22 Johns Hopkins undergraduates took part in this study for course-related credit. The experiment was run in parallel with Experiment 3, reported below. All the participants had normal or corrected-to-normal vision. All study procedures were approved and conducted in compliance with the guidelines provided by the Homewood Institutional Review Board (HIRB).

Stimuli and Procedure

A cue appeared during the 2nd frame of the ISI after the 6th, 10th, 14th, 18th, or 22nd letter in the RSVP stream of a given trial. The cue lasted for one display frame. An illustration of the paradigm is shown in Figure 4.

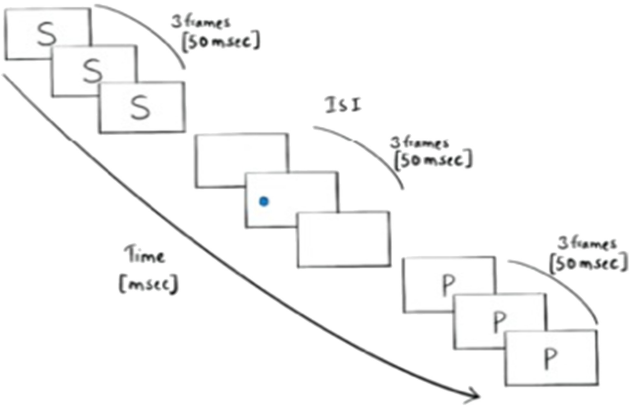
Results

Although there were no technically correct responses in this experiment, we nonetheless coded responses in terms of SPEs—the ordinal position of the letter reported relative to the cue onset. No responses were coded as having an SPE of 0, since no letter was ever actually present together with the cue. Again, negative numbers referred to letters that preceded a cue, and positive numbers to letters that followed a cue. As in Experiment 1, we pooled responses across all participants by visual eccentricity to generate a distribution of SPEs, shown in Figure 5.

Mauchly's sphericity and Levene's homoscedasticity tests of the data conformed with ANOVA assumptions. A repeated measures ANOVA revealed a significant difference between responses for the 2° and 10° conditions across participants, $F(1, 21) = 9.96$, $p = .005$, $\eta_p^2 = 0.32$ (see Figure 6). Further, a post hoc paired t-test analysis revealed a statistically significant difference between the SPE reports of 2° ($M = 0.31$, $SD = 0.52$) and the 10° conditions ($M = 0.01$, $SD = 0.52$); $t(21) = 3.15$, $p = .004$. In the 2° condition, participants reported letters that followed the cue more frequently than they did in the 10° condition.

Figure 4

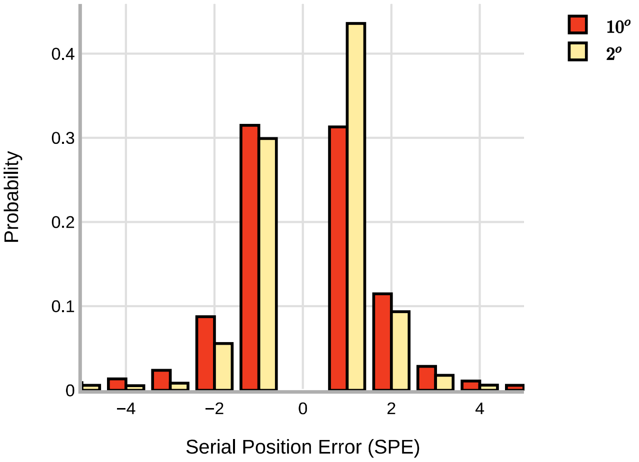
RSVP Task Used in Experiment 2



Note. The cue would always appear for 1 frame duration in the middle of the 3 frame interstimulus interval (ISI) of the two letters in the stream. The cue could appear either 2° or 10° to the left/right of the fixation.

Figure 5

Results of Experiment 2



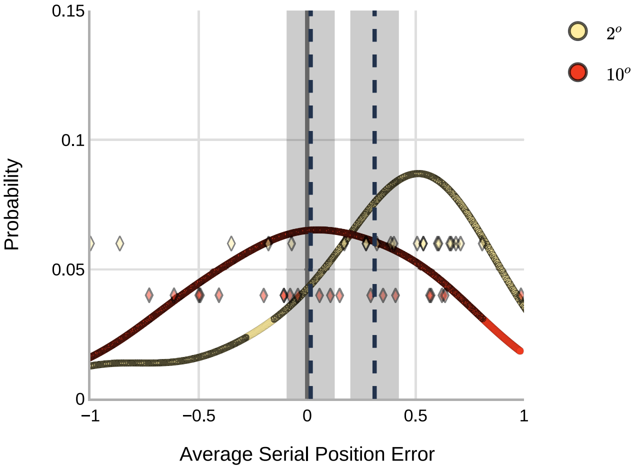
Note. See the online article for the color version of this figure.

Discussion

These results converge on the hypothesis that more peripheral cues are perceived, on average, faster than more central cues. Because there was no right answer in this experiment, these results further suggest a (perhaps unsurprising) general tendency to report letters that follow the cue, a tendency that makes the *negative* average SPE in the 10° condition of Experiment 1 more compelling. More so than in Experiment 1, these can be described aptly as a disadvantage for central processing compared with relatively

Figure 6

Results of Experiment 2



Note. The curves represent the probability density. Each diamond is an individual participant SPE average by condition. Dashed lines show means by conditions, with shade to show the standard error of means. See the online article for the color version of this figure.

accurate peripheral processing. Yet we remain hesitant to apply characterization in terms of objectively inaccurate or disadvantaged perception since the methods here and in Experiment 1 were designed primarily to allow for comparisons between the probe conditions. Accordingly, what we continue to emphasize is that SPEs in the more central cue condition were again more positive as compared to those in the peripheral condition.

Experiment 3: A Control for Distance Versus Eccentricity

This experiment sought to establish that the effects observed so far were caused by the relative eccentricities of the cues, not the distances between the cues and the RSVP stream. In Experiment 1, a more eccentric cue was also more distant from the RSVP stream, which was itself at fixation. Here, we utilized a central fixation cross with the RSVP stream presented on one side of the screen and the cue appearing at an unpredictable time on the other side of the screen. In each trial, cue and RSVP were therefore always equidistant from fixation, each either 1° or 5° away. This amounted to half of the trials including an RSVP stream and a cue location that were 2° apart, and the remaining half of the trials including an RSVP stream and a cue location that were 10° apart. But in every individual trial, the cue and the stream were equally eccentric. Figure 7 schematizes the methods of this experiment.

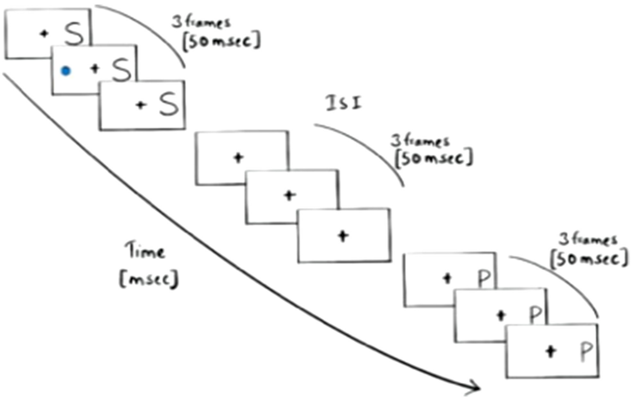
If a greater distance separating a cue and an RSVP presentation cause more preceding letter reports (more negative SPEs) then we should observe attendant effects in the current experiment. However, if an increase in the tendency to report preceding letters is caused by the *relative* eccentricity of the cue compared to a stream, then no such effects should be observed in this experiment. Put slightly differently, if distance is not a key determinant of speed to perceptual access, but eccentricity is, then a cue and a letter that onset at the same time in this experiment should run the race to perceptual access at the same speed, on average, thereby arriving at the same time (on average) regardless of the distance that separates them from one another.

Method

The experiment was identical to Experiment 1, except as follows.

Figure 7

RSVP task used in Experiment 3



Note. In each trial, the cue and the letter stream were placed opposite from each other and equidistant from the fixation cross, either 1° or 5° away.

Participants

Twenty-five Johns Hopkins undergraduates took part in this study for course-related credit.

Stimuli and Procedure

The letter stream and the cue were presented 1° and 5° of visual angle apart from fixation on opposite sides. The overall distance between the letter stream and the cue was always either 2° (half of trials), or 10° (the remaining half of the trials). The stream appeared left of fixation in half of the trials and right of fixation in the remaining half.

Results

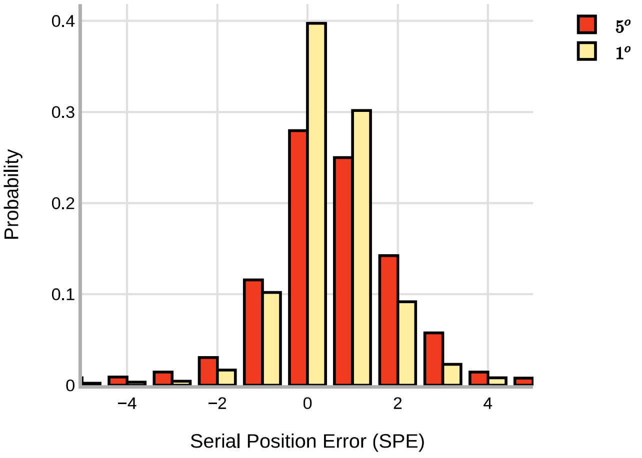
Participant responses were coded as SPEs exactly as in Experiment 1. Figure 8 shows the distribution of SPEs pooled across all trials and participants. Mauchly's sphericity and Levene's homoscedasticity tests of the data conformed with ANOVA assumptions. A repeated measures ANOVA analysis indicated that the difference between the responses for the 1° and 5° conditions was not statistically significant across participants, $F(1, 24) = 1.522$, $p = .22$, $\eta_p^2 = 0.05$ (see Figure 9). Additionally, a one-sample *t*-test revealed that the distributions for the 1° and 5° were significantly different than 0; 1°: $t(24) = 4.5$, $p < .001$; 5°: $t(24) = 4.3$, $p < .001$, respectively.

Discussion

Two aspects of the results in this experiment are of interest. The first, a somewhat incidental result, is that in both conditions average SPEs were positive. When the locations of a cue and an RSVP stream do not overlap, and absent an eccentricity difference, responses tend toward letters that follow the cue as opposed to letters that precede it. As a baseline, then, any manipulation that pulls responses toward cue-preceding letters must work against the current, so to speak. Particularly in Experiment 2, this can explain why the effect manifested as an average SPE close to zero for more eccentric cues, compared to a positive SPE for less eccentric ones.

Figure 8

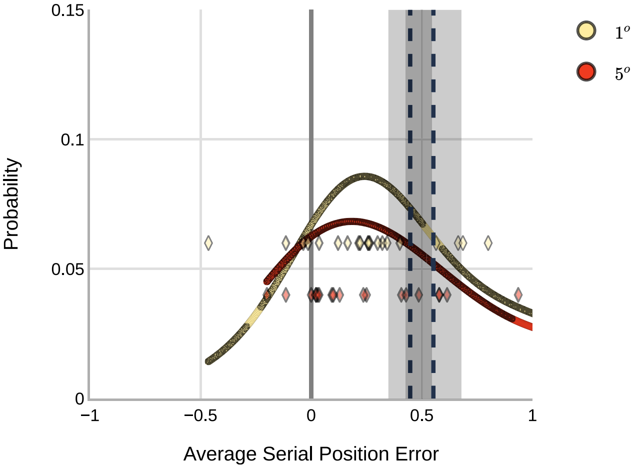
Results of Experiment 3



Note. See the online article for the color version of this figure.

Figure 9

Results of Experiment 3



Note. The curves represent the probability density. Each diamond is an individual participant SPE average by condition. Dashed lines show means by conditions, with shade to show the standard error of means. See the online article for the color version of this figure.

More directly relevant for control purposes, there was no significant difference in average SPEs between the conditions in the current experiment. Within each trial of this experiment, the cue and RSVP letter stream were placed at the same eccentricity. However, across trials their distances from one another varied. The lack of effect thereby demonstrates that the distance between a cue and the RSVP letter stream cannot be the cause of the previous effects. Cues that were more distant from the stream led to letter responses which were no different from responses to cues that were closer.

Experiment 4: Eccentricity Elongates Perceived Duration

Carrasco and colleagues (2003) predicted that speed of processing advantages in the periphery should have perceptual consequences. The experiments reported thus far document one such consequence. Using an RSVP paradigm, we demonstrated a relative speed advantage in the periphery for the time it takes for a stimulus to be perceived, along with attendant occasions of misperceived simultaneity between periphery and fovea.

In our final experiment, we sought to document a second perceptual difference between periphery and fovea, a difference regarding perceived duration. We were motivated by the expectation that temporal processing differences across the visual field should have pervasive consequences (Carrasco et al., 2003). Duration is of interest, in particular, as an influential literature has documented variability in duration perception as a function of many factors including, for example, expectation, novelty, arousal, emotional state, and attention (Allman et al., 2014; Eagleman & Pariyadath, 2009; Fraisse, 1984; Pariyadath et al., 2007, 2012; Pariyadath & Eagleman, 2008; Phillips, 2013; Tse et al., 2004; see Wearden, 2016 for a review).

Specifically, we sought to determine whether, all else being equal, the eccentricity of a stimulus affects how long it is perceived to last. Our primary hypothesis was just that there would be a difference between the reported perceived durations of more and less eccentric stimuli. However, we also had a tentative directional hypothesis: that more eccentric stimuli would be perceived as lasting longer than less eccentric stimuli with objectively equal durations. Our reasoning was based on models of duration perception that depend on the accumulation of units of perceptual processing. Rapid temporal processing in the periphery might accumulate more pulses compared to the fovea for a given duration. Accordingly, this could result in a longer duration judgment in the periphery compared to the fovea. There was some disagreement among researchers, however, and as already noted, our key prediction was non-directional. We, therefore, reserve for the discussion further explication of our secondary, directional hypothesis.

To measure perceived duration, we employed a widely used duration reproduction approach (see Figure 10). Participants were instructed to fixate on the center of the screen. A disc then appeared on the screen on the horizontal meridian away from the fixation for a given amount of time. Participants were instructed to reproduce the disc duration by pressing and holding the space bar. The location of presentation varied from trial to trial.

Method

Participants

Twenty-three Johns Hopkins undergraduates participated for course-related credit. We modeled our methods on a report by Tse et al. (2004). That study included six observers with long psychophysical experimental sessions. We tested participants in sessions with roughly half as many trials, and therefore we sought to test roughly four times as many participants in the lab. All participants reported normal or corrected-to-normal vision.

Materials

Stimuli were generated with Psychopy3 and presented on a 27-in. display with a refresh rate of 60 Hz (16.667 ms/frame). Participants

Figure 10

Schematic Depiction of Experiment 4

Note. In each trial a disc appeared in one of the four possible locations along the horizontal axis for a given duration which was reproduced by pressing the spacebar. Gray icons (which were not present in the experiment) represent possible locations in the example shown.

were seated approximately 55 cm away from the monitor, so that the display occupied about 46° × 29° in visual angle.

Stimuli and Procedure

Each trial in this experiment included a black disc that appeared on the horizontal axis of the screen and then disappeared. The task for participants was to report the duration of the disc in that trial by pressing and holding the space bar for the same duration (after the disc disappeared; see Figure 10).

Each disc was 1.06° in diameter and fully black against a white background. Once it appeared, a disc remained present for one of ten predetermined durations ranging from under one second to one and a half seconds, specifically: 750, 825, 900, 975, 1,050, 1,125, 1,250, 1,375, 1,450, or 1,525 ms. The disc could appear in one of four screen locations, either 3° or 12° to the left or right of fixation. Each experimental session included a total of 240 trials divided equally between all combinations of four locations and ten durations, randomly ordered and counterbalanced.

Participants were told that they would be judging the duration of the disc in each trial. They were told to always fixate the center of the screen during a trial (although fixation was not monitored or enforced). Once the disc disappeared a participant would reproduce its present duration by holding down the spacebar (i.e., pressing to initiate, holding, and then releasing to end the reproduced duration). Participants were awarded points in each trial based on how close a response was to the actual duration. The number of points earned in a trial decreased logarithmically as a function of the difference between reproduced and objective duration. To encourage sustained attention and good performance, participants were told that they would receive double credit for the experiment should they collect over 1,900/2,400 total points. (Each of the 240 trials was for 10 points. Ultimately, all participants were awarded double credit regardless of score.)

Results

The raw data is shown in Figure 11A. We pooled all the data by the eccentricity and the duration condition. Within each condition, we excluded data points that were over the 5% and the 95% quantiles. This led to the removal of 10.1% of the data overall across all the conditions. Further, we used the average reproduced duration for the 750 ms condition for each eccentricity condition across participants as a baseline. This was done in order to account for any internal representations of noise across the conditions. Thus, all the responses for the remaining 9 duration conditions across the two eccentricities included their respective baselines subtracted from the original responses. Mauchly's sphericity and Levene's homoscedasticity tests of the data conformed with ANOVA assumptions. A repeated measures ANOVA with eccentricity and duration as the two factors revealed a main effect of eccentricity condition, $F(1, 22) = 8.10$, $p < .001$, $\eta_p^2 = 0.26$, and a main effect of duration, $F(8, 176) = 225.13$, $p < .001$, $\eta_p^2 = 0.91$. There was no significant interaction between eccentricity and duration, $F(8, 176) = 1.37$, $p = .2$, $\eta_p^2 = 0.058$. Overall, the responses in both the eccentricity conditions across all the durations were under reproduced as can be seen in Figure 11B. Post hoc paired t-test analysis revealed a statistically significant difference in responses between the 3° ($M =$ 1.015 s, $SD = 0.18$) and 12° ($M = 1.058$ s, $SD = 0.18$) conditions $t(22) = -2.848$, $p \leq .009$ (see Figure 12). These results suggest that perceived duration is affected by the eccentricity at which the stimulus was presented.

Discussion

The key result of this experiment is that stimuli which last (objectively) equal durations are perceived as lasting different durations depending on their position relative to fixation. Specifically, more eccentric stimuli are perceived as lasting longer than less eccentric ones. Why is this the direction of the effect? The reproduction task used here has been used elsewhere to investigate the plasticity of duration perception. (One minor novelty in the present experiments was that participants were rewarded for good performance. However, we see no reason to think that this is of any significance in the present context.) An important set of findings from such studies suggests that unusual or unexpected stimuli are perceived as lasting longer than their typical counterparts (Eagleman & Pariyadath, 2009; Pariyadath & Eagleman, 2008; Pariyadath et al., 2007, 2012; Tse et al., 2004). Explanations for these effects often appeal to a mediating effect of attention (Tse et al., 2004). And more broadly, these accounts assume that the amount of accumulated processing associated with a stimulus ends up as a proportional and reportable proxy for the perceived stimulus duration (Mauk, & Buonomano, 2004; Block & Reed, 1978; Brown, 1995; Poynter, 1989).

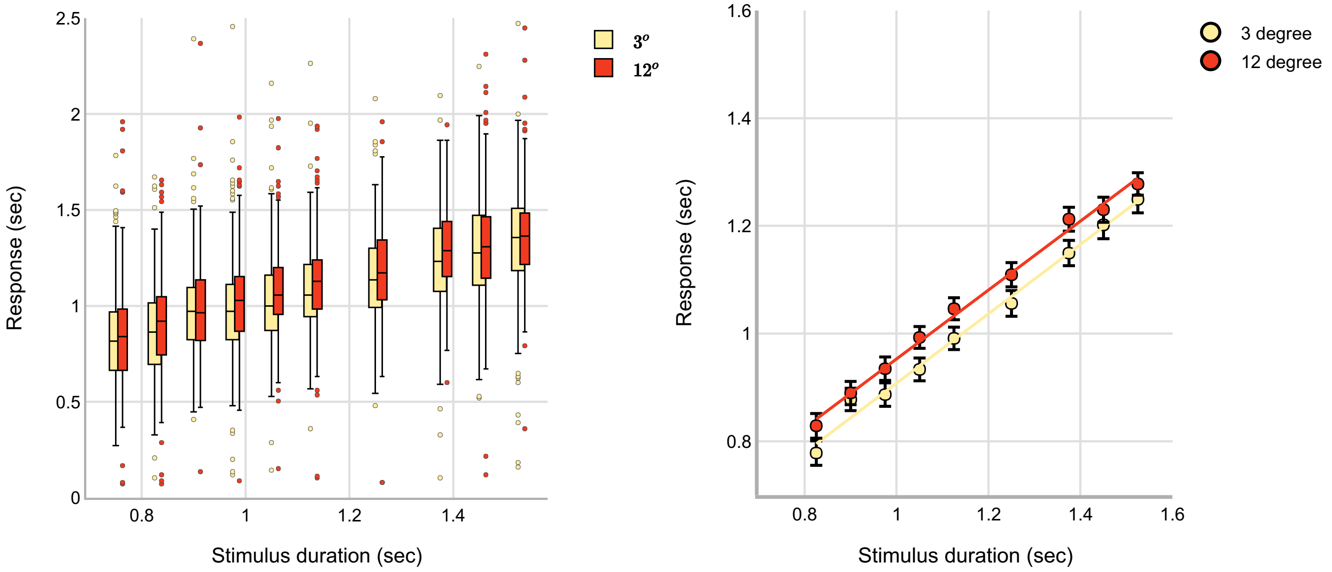
Here we anticipated the outcome of the experiment by reasoning that faster integration of a stimulus in the periphery could result in more accumulated pulses of processing. Put slightly differently, if we think of a stimulus as evoking not just one signal, but several instead, then we can speculate that the number of signals processed fully over a given period should be proportional to the rate at which the relevant signals get processed. If peripheral signals are processed more quickly than foveal ones, then more of them should be processed over a limited duration. A result that we had not anticipated—but one that follows as well—is that events in the periphery should yield more accurate duration estimates. Indeed, the results obtained are consistent with the idea that enhanced peripheral sampling produces a smaller total amount of error and reproductions that were closer to the objective stimulus. This also suggests that temporal processing differences between the periphery and the fovea may have functional roles, with the periphery detecting fast signals more quickly and producing a more accurate impression of duration. Evidently, this is nevertheless a speculative explanation of a new and surprising result. Minimally, then, our experiment highlights the need for further investigation into a potentially wide range of differences in temporal processing across the visual field.

General Discussion

Across four experiments we investigated temporal perception along the horizontal meridian of a viewer's field of vision. Our investigation was motivated by the well-characterized radial nonuniformity in receptor distribution in the human visual system, attendant spatial processing differences, and in particular by recent reports of faster processing speeds at more eccentric positions (Carrasco et al., 2003; Jovanovic & Mamassian, 2020a). Experiments 1 and 2 demonstrate that an item onsetting in the periphery advances to perception faster than an item nearer to the fovea. Experiment 3 identifies eccentricity as opposed to distance

Figure 11

Results of Experiment 4

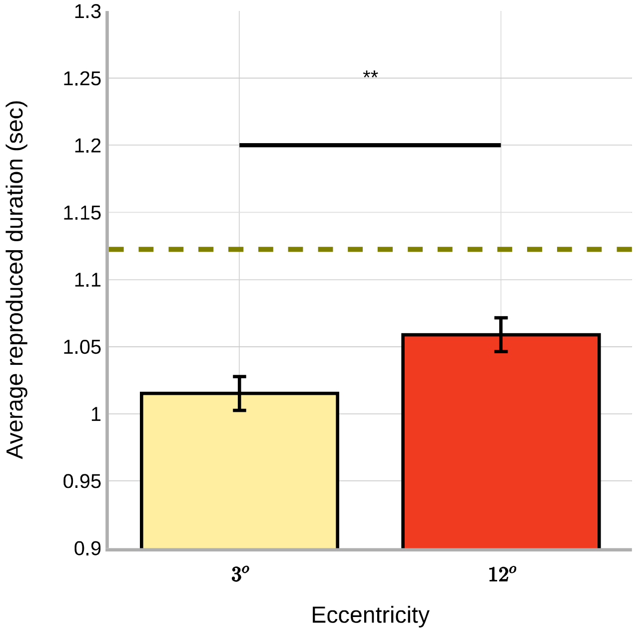


Note. (Panel A) Boxplot showing the distribution of reproduced durations as a function of objective duration and distance condition across all participants. Whiskers show upper and lower quartiles. (Panel B) Responses accounting for the lowest duration reports (750 ms) as a baseline for the internal noise within subjects. Solid lines indicate the model fit. The error bars indicate the 95% CI of the mean. See the online article for the color version of this figure.

as the key variable. Experiment 4 demonstrates a further temporal difference between more and less peripheral locations, an expansion in perceived duration for more eccentric stimuli compared to less eccentric ones.

Figure 12

Results of Experiment 4



Note. The dotted line represents the average objective duration of about 1.12 s. See the online article for the color version of this figure.

One outstanding issue is whether spatial shifts of attention could account for the reported results. We discuss this in the next section. We then conclude by exploring the broader implications of our findings with respect to the nature of time perception in human vision.

Alternative Mechanisms: Attention Shifts, Saccades, and Prior Entry

Moving eyes between two points take time to traverse the space. Since fixation was not enforced in these experiments, we should consider how eye movements away from the central RSVP stream (Experiments 1 and 2) could impact the results. Suppose that occasionally a participant shifts their fixation away from the RSVP stream to the location of the probe, upon its appearance. If the participant does not shift their eyes back to the RSVP stream, they may retain a memory for a letter that appeared *prior* to the probe onset, a memory that could then drive a response. Even if they do shift their eyes back to the RSVP stream, the likelihood of saccadic suppression during both eye movements might push responses toward recent memory as opposed to perceptions that follow probe onset. However, because such mechanisms would predict a baseline bias toward letters that precede probe onset, they cannot explain the key results from Experiment 3 (see Figure 9), where all else equal, we observed biases toward letters that *succeeded* the probe. The data thus do not support the view that participants generally relied on RSVP-related memory preceding probe onsets.

One might also think that eye movements could explain the observed bias toward succeeding letters. This would be the case if, having made a saccade to the probe, a participant shifts back to the RSVP to collect a letter for response. Note that this kind of shift toward and away could occur even without a physical eye movement. Classic research has shown that it can take time to shift attention spatially

(Posner, 1980; but see Eimer & Grubert, 2014). It is therefore worth considering whether successive shifts of the eyes or of attention may account for the results of Experiments 1 and 2.

Suppose that an observer shifts attention away from the central RSVP stream and to the location of a cue when it appears transiently. Because the more eccentric cues are farther away from the origin than are the less eccentric cues, it should take *more* time to complete such a shift. Now suppose that having shifted attention and having thus confirmed the arrival of the transient cue, that the observer shifts back to the RSVP stream in order to identify the letter present. In general, such shifts, whether of attention or physical eye movements, should bias responses toward letters that *succeed* the cue and away from letters that precede it. Indeed, such behavior may account for the fact that we observed a general bias toward letters that succeed the cue in Experiment 3, where eccentricity and relative distance were controlled. It may also explain why the average SPE in the more eccentric condition of Experiment 2 was indistinguishable from zero (see Figure 6). This is what we would expect if eccentric cues pushed responses toward earlier letters, but attention shifts countervail, pulling them in the opposite direction.

Critically, however, shifts of overt or covert attention cannot explain the key differences we observed between more and less eccentric cue positions. If time to shift is proportional to distance traversed, then the round trip from RSVP letter stream to cue and back should take *longer* for more eccentric cue positions, thereby producing a greater bias toward letters that *succeed* the cue. Yet we observed just the opposite tendency: to report relatively *preceding* letters more when the cue was more eccentric. We suspect that occasional shifts of attention or eyes did work against the observed effects to some degree, potentially causing them to be smaller than they would otherwise have been. But despite this, a clear SPE difference between eccentricity conditions emerged in both experiments.

Another potential effect worth considering is prior entry. Indeed, our initial motivation to investigate misperceived timing relations came from the literature on prior entry, and the related topics of simultaneity perception, and temporal order judgment (Frey, 1990; Jaśkowski, 1993; Stelmach & Herdman, 1991; Sternberg & Knoll, 1973; see also Spence & Parise, 2010 for a review on prior entry and Vroomen & Keetels, 2010 for a tutorial on temporal order judgments). Prior entry is a phenomenon where an attended stimulus is processed faster compared to the unattended stimulus (Titchener, 1908). This phenomenon has been extensively studied using temporal order judgment paradigms (Klein et al., 1998; Scharlau, 2007; Shore et al., 2001; Spence et al., 2001).

If an observer attends to the central RSVP stream, then prior entry predicts that when a cue appears in an unattended location, the cue would be processed more slowly than the current letter. As a result of having been processed more slowly, such a cue would be reported with future letters in the stream. Therefore, responses, in general, would be biased toward letters that *succeed* the current letter. We observed the opposite tendency, that is, a bias toward letters which *preceded* the current letter when accompanied by more eccentric cues.

A related alternative account could appeal to capture together with prior entry: the transient nature of the cues may capture an observer's attention (Johnston et al., 1990). A cue that captures attention should be processed faster because of prior entry, compared to the current letter in the RSVP stream. Such an account would predict preceding letters to be reported with the cue. To explain the results of Experiments 1 and 2 however, the account would require an ad hoc explanation for why more eccentric cues produce more capture, that is in order to explain the difference between eccentricity conditions. Moreover, transient capture and prior entry account are incommensurate with the results of Experiment 3, where responses were biased toward succeeding (not preceding) letters, suggesting a baseline lack of capture aided prior entry for the transient cues.

For these reasons, the SPE difference between eccentricity conditions which we observed is, in our view, best characterized in terms of a race to perception, whereby a more eccentric cue runs faster than a less eccentric cue and faster also than the centrally presented RSVP letters. As a result, more eccentric cues more often arrive at the finish line together with RSVP letters which in fact preceded them objectively: letters that in the race analogy, had a head start but ran slowly and were caught.

The Perception of Time Across Space

Differences in transmission and processing speed across modalities present a well-known challenge to the perceptual system, and translate into misperceptions of simultaneity (for reviews, see Paraskevoudi & Vatakis, 2019; Spence & Squire, 2003; Vroomen & Keetels, 2010). For instance, sound waves propagate much slower than light. Despite this, in the presence of robust distance cues, the perceptual system can compensate for significant discrepancies in signal arrival times to accurately represent objective timing (Alais & Carlile, 2005). However, such compensatory mechanisms are not always successful: notoriously, we see the lightning long before we hear the thunder. In contrast, auditory processing is significantly faster than visual processing. This provides a natural explanation of the finding that (for most observers) the optimal conditions for perceived simultaneity occur with visual stimuli preceding auditory stimuli (Stone et al., 2001; W. F. Smith, 1933). Although less well-studied, similar effects are found between other modalities. For instance, Roy et al. (2017) found that perceptual synchrony was optimally achieved when tactile stimuli preceded auditory stimuli by 40–80 ms.

Differential processing latencies also affect time perception for different features within a modality. For example, Moutoussis and Zeki (1997) showed subjects groups of moving colored squares which collectively changed color and direction. In some trials these changes occurred simultaneously, in others they were out of sync. For motion and color changes to appear as simultaneous, the color change needed to occur approximately 100 ms before the motion direction change. In other words: object–color is perceived approximately 100 ms before direction of motion, a finding that Moutoussis and Zeki attribute to differences in the latencies associated with the specialized visual systems for processing the two features. Clifford and colleagues (2003) report a closely related, albeit more complex, phenomenon concerning the perception of changes in orientation and color—again, in part, attributing the effect to differences in neuronal latencies.

The results presented here, along with other recent reports of temporal processing differences across the visual field (Carrasco et al., 2003; Giordano et al., 2004; Jovanovic & Mamassian, 2020a, 2020b), suggest that, in the very same way, differences in processing latencies associated with spatial position translate into misperceptions of simultaneity between items that never coincided objectively. Even more strikingly, our results suggest that such processing differences also affect our experience of duration. That is, the experience of an objectively continuous duration during which an object is present yields differing impressions depending on where in the visual field the object appeared.

Many questions remain both in detail and theory. For example, could timing-contingent overlap in cortical processing be a contributing mechanism to the effects that we and others have observed (Stewart et al., 2020)? Might faster processing speeds in the periphery play a functional role, affording a quick detection mechanism, for example, of either important or simply fast-moving stimuli (Rosenholtz, 2016)? How does duration perception interact with motion perception across the visual field? Does location interact with the speed at which continuous changes to objects are perceived and with how multiple changes become registered as simultaneous? Do mechanisms within the visual system attempt to compensate for the differences in processing across spatial locations? And what other factors modulate the effect of location on perceived simultaneity? A great deal of future research will be needed to resolve these and many other related questions.

Transparency and Openness Disclosures

(Also appended to the methods of Experiment 1). The authors designed all the methods and wrote associated code for the experiments reported. Experimental code, analysis scripts, and raw data are made publicly and permanently available through the OSF repository (https://osf.io/q9kun/). All study measures and analyses conducted are reported in the text. There were no participant exclusions. As described along with the associated experiments, some sample sizes were constrained by COVID-19-related circumstances which halted data collection. However, no data were analyzed until the research team agreed that no more data would be collected in each experiment. Analysis plans and methods were not pre-registered, but closely followed the analyses applied in cited literature with similar methods.

References

Alais, D., & Carlile, S. (2005). Synchronizing to real events: Subjective audiovisual alignment scales with perceived auditory depth and speed of sound. *Proceedings of the National Academy of Sciences*, *102*(6), 2244–2247. https://doi.org/10.1073/pnas.0407034102

Allman, M. J., Teki, S., Griffiths, T. D., & Meck, W. H. (2014). Properties of the internal clock: First-and second-order principles of subjective time. *Annual Review of Psychology*, *65*(1), 743–771. https://doi.org/10.1146/annurev-psych-010213-115117

Block, R. A., & Reed, M. A. (1978). Remembered duration: Evidence for a contextual-change hypothesis. *Journal of Experimental Psychology: Human Learning and Memory*, *4*(6), 656–665. https://doi.org/10.1037/0278-7393.4.6.656

Brown, S. W. (1995). Time, change, and motion: The effects of stimulus movement on temporal perception. *Perception and Psychophysics*, *57*(1), 105–116. https://doi.org/10.3758/BF03211853

Callahan-Flintoft, C., Holcombe, A. O., & Wyble, B. (2020). A delay in sampling information from temporally autocorrelated visual stimuli. *Nature Communications*, *11*(1), 1–11. https://doi.org/10.1038/s41467-020-15675-1

Carrasco, M., McElree, B., Denisova, K., & Giordano, A. M. (2003). Speed of visual processing increases with eccentricity. *Nature Neuroscience*, *6*(7), 699–700. https://doi.org/10.1038/nn1079

Chun, M. M., & Potter, M. C. (1995). A two-stage model for multiple target detection in rapid serial visual presentation. *Journal of Experimental Psychology: Human Perception and Performance*, *21*(1), 109–127. https://doi.org/10.1037//0096-1523.21.1.109

Clifford, C. W., Arnold, D. H., & Pearson, J. (2003). A paradox of temporal perception revealed by a stimulus oscillating in colour and orientation. *Vision Research*, *43*(21), 2245–2253. https://doi.org/10.1016/S0042-6989(03)00120-2

Eagleman, D. M., & Pariyadath, V. (2009). Is subjective duration a signature of coding efficiency? *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1525), 1841–1851. https://doi.org/10.1098/rstb.2009.0026

Eimer, M., & Grubert, A. (2014). Spatial attention can be allocated rapidly and in parallel to new visual objects. *Current Biology*, *24*(2), 193–198. https://doi.org/10.1016/j.cub.2013.12.001

Fehd, H. M., & Seiffert, A. E. (2008). Eye movements during multiple object tracking: Where do participants look? *Cognition*, *108*(1), 201–209. https://doi.org/10.1016/j.cognition.2007.11.008

Fehd, H. M., & Seiffert, A. E. (2010). Looking at the center of the targets helps multiple object tracking. *Journal of Vision*, *10*(4), 19.1–19.13. https://doi.org/10.1167/10.4.19

Fraisse, P. (1984). Perception and estimation of time. *Annual Review of Psychology*, *35*(1), 1–37. https://doi.org/10.1146/annurev.ps.35.020184.000245

Frey, R. D. (1990). Selective attention, event perception and the criterion of acceptability principle: Evidence supporting and rejecting the doctrine of prior entry. *Human Movement Science*, *9*(3–5), 481–530. https://doi.org/10.1016/0167-9457(90)90012-3

Giordano, A., McElree, B., & Carrasco, M. (2004). On the automaticity and flexibility of covert attention. *Journal of Vision*, *4*(8), Article 627. https://doi.org/10.1167/4.8.627

Goodbourn, P. T., & Holcombe, A. O. (2015). "Pseudoextinction": Asymmetries in simultaneous attentional selection. *Journal of Experimental Psychology: Human Perception and Performance*, *41*(2), 364–384. https://doi.org/10.1037/a0038734

Goodbourn, P. T., Martini, P., Barnett-Cowan, M., Harris, I. M., Livesey, E. J., & Holcombe, A. O. (2016). Reconsidering temporal selection in the attentional blink. *Psychological Science*, *27*(8), 1146–1156. https://doi.org/10.1177/0956797616654131

Hartmann, E., Lachenmayr, B., & Brettel, H. (1979). The peripheral critical flicker frequency. *Vision Research*, *19*(9), 1019–1023. https://doi.org/10.1016/0042-6989(79)90227-X

Henderson, J. M., & Hollingworth, A. (2003). Global transsaccadic change blindness during scene perception. *Psychological Science*, *14*(5), 493–497. https://doi.org/10.1111/1467-9280.02459

Himmelberg, M. M., & Wade, A. R. (2019). Eccentricity-dependent temporal contrast tuning in human visual cortex measured with fMRI. *NeuroImage*, *184*(1), 462–474. https://doi.org/10.1016/j.neuroimage.2018.09.049

Jaśkowski, P. (1993). Selective attention and temporal-order judgment. *Perception*, *22*(6), 681–689. https://doi.org/10.1068/p220681

Johnston, W. A., Hawley, K. J., Plewe, S. H., Elliott, J. M., & DeWitt, M. J. (1990). Attention capture by novel stimuli. *Journal of Experimental Psychology: General*, *119*(4), 397–411. https://doi.org/10.1037/0096-3445.119.4.397

Jovanovic, L., & Mamassian, P. (2020a). Events are perceived earlier in peripheral vision. *Current Biology*, *30*(21), R1299–R1300. https://doi.org/10.1016/j.cub.2020.08.096

Jovanovic, L., & Mamassian, P. (2020b). Temporal context affects the perceived time of visual events. *Psychonomic Bulletin & Review*, *27*(1), 56–61. https://doi.org/10.3758/s13423-019-01682-x

Klein, R. M., Schmidt, W. C., & Müller, H. J. (1998). Disinhibition of return: Unnecessary and unlikely. *Perception and Psychophysics*, *60*(5), 862–872. https://doi.org/10.3758/BF03206069

Kolb, H. (2011). *Gross anatomy of the eye*. University of Utah Health Sciences Center.

Levi, D. M. (2008). Crowding—an essential bottleneck for object recognition: A mini-review. *Vision Research*, *48*(5), 635–654. https://doi.org/10.1016/j.visres.2007.12.009

Mauk, M. D., & Buonomano, D. V. (2004). The neural basis of temporal processing. *Annual Review of Neuroscience*, *27*(1), 307–340. https://doi.org/10.1146/annurev.neuro.27.070203.144247

Moutoussis, K., & Zeki, S. (1997). A direct demonstration of perceptual asynchrony in vision. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, *264*(1380), 393–399. https://doi.org/10.1098/rspb.1997.0056

Paraskevoudi, N., & Vatakis, A. (2019). When the perception of a synchronous world is—Mostly—Just an illusion. In V. Arstila, A. Bardon, S. E. Power, & A. Vatakis (Eds.), *The illusions of time* (pp. 225–257). Springer.

Pariyadath, V., Eagleman, D., & Burr, D. (2007). The effect of predictability on subjective duration. *PLoS One*, *2*(11), Article e1264. https://doi.org/10.1371/journal.pone.0001264

Pariyadath, V., & Eagleman, D. M. (2008). Brief subjective durations contract with repetition. *Journal of Vision*, *8*(16), Article 11. https://doi.org/10.1167/8.16.11

Pariyadath, V., Eagleman, D. M., & Wennekers, T. (2012). Subjective duration distortions mirror neural repetition suppression. *PLoS One*, *7*(12), Article e49362. https://doi.org/10.1371/journal.pone.0049362

Phillips, I. (2013). XII—Perceiving the passing of time. *Proceedings of the Aristotelian Society (Hardback)*, *113*(3pt3), 225–252. https://doi.org/10.1111/j.1467-9264.2013.00353.x

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*(1), 3–25. https://doi.org/10.1080/00335558008248231

Poynter, D. (1989). Judging the duration of time intervals: A process of remembering segments of experience. In I. Levin & D. Zakay (Eds.), *Time and human cognition: A life-span perspective* (Vol. 59, pp. 305–331). Elsevier.

Raymond, J. E., Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink? *Journal of Experimental Psychology: Human Perception and Performance*, *18*(3), 849–860. https://doi.org/10.1037//0096-1523.18.3.849

Rayner, K. (1975). The perceptual span and peripheral cues in reading. *Cognitive Psychology*, *7*(1), 65–81. https://doi.org/10.1016/0010-0285(75)90005-5

Rayner, K., Pollatsek, A., Ashby, J., & Clifton C. (2012). *Psychology of reading*. Psychology Press.

Rosenholtz, R. (2016). Capabilities and limitations of peripheral vision. *Annual Review of Vision Science*, *2*(1), 437–457. https://doi.org/10.1146/annurev-vision-082114-035733

Rovamo, J., & Raninen, A. (1984). Critical flicker frequency and M-scaling of stimulus size and retinal illuminance. *Vision Research*, *24*(10), 1127–1131. https://doi.org/10.1016/0042-6989(84)90166-4

Roy, C., Dalla Bella, S., & Lagarde, J. (2017). To bridge or not to bridge the multisensory time gap: Bimanual coordination to sound and touch with temporal lags. *Experimental Brain Research*, *235*(1), 135–151. https://doi.org/10.1007/s00221-016-4776-4

Scharlau, I. (2007). Perceptual latency priming: A measure of attentional facilitation. *Psychological Research*, *71*(6), 678–686. https://doi.org/10.1007/s00426-006-0056-4

Shore, D. I., Spence, C., & Klein, R. M. (2001). Visual prior entry. *Psychological Science*, *12*(3), 205–212. https://doi.org/10.1111/1467-9280.00337

Sinha, R., Hoon, M., Baudin, J., Okawa, H., Wong, R. O. L., & Rieke, F. (2017). Cellular and circuit mechanisms shaping the perceptual properties of the primate fovea. *Cell*, *168*(3), 413–426.e12. https://doi.org/10.1016/j.cell.2017.01.005

Smith, T. J., Lamont, P., & Henderson, J. M. (2012). The penny drops: Change blindness at fixation. *Perception*, *41*(4), 489–492. https://doi.org/10.1068/p7092

Smith, W. F. (1933). The relative quickness of visual and auditory perception. *Journal of Experimental Psychology*, *16*(2), 239–257. https://doi.org/10.1037/h0071379

Spence, C., & Parise, C. (2010). Prior-entry: A review. *Consciousness and Cognition*, *19*(1), 364–379. https://doi.org/10.1016/j.concog.2009.12.001

Spence, C., Shore, D. I., & Klein, R. M. (2001). Multisensory prior entry. *Journal of Experimental Psychology: General*, *130*(4), 799–832. https://doi.org/10.1037/0096-3445.130.4.799

Spence, C., & Squire, S. (2003). Multisensory integration: Maintaining the perception of synchrony. *Current Biology*, *13*(13), R519–R521. https://doi.org/10.1016/S0960-9822(03)00445-7

Stelmach, L. B., & Herdman, C. M. (1991). Directed attention and perception of temporal order. *Journal of Experimental Psychology: Human Perception and Performance*, *17*(2), 539–550. https://doi.org/10.1037/0096-1523.17.2.539

Sternberg, S., Knoll, R. L. (1973). The perception of temporal order: Fundamental issues and a general model. In S. Kornblum (Ed.), *Attention and performance IV* (pp. 629–685). Academic Press.

Stewart, E. E. M., Valsecchi, M., & Schütz, A. C. (2020). A review of interactions between peripheral and foveal vision. *Journal of Vision*, *20*(12), Article 2. https://doi.org/10.1167/jov.20.12.2

Stone, J., Hunkin, N., Porrill, J., Wood, R., Keeler, V., Beanland, M., Port, M., & Porter, N. (2001). When is now? Perception of simultaneity. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, *268*(1462), 31–38. https://doi.org/10.1098/rspb.2000.1326

Titchener, E. B. (1908). *Lectures on the elementary psychology of feeling and attention*. Macmillan.

Tse, P. U., Intriligator, J., Rivest, J., & Cavanagh, P. (2004). Attention and the subjective expansion of time. *Perception and Psychophysics*, *66*(7), 1171–1189. https://doi.org/10.3758/bf03196844

Upadhyayula, A., & Flombaum, J. (2020). A model that adopts human fixations explains individual differences in multiple object tracking. *Cognition*, *205*, Article 104418. https://doi.org/10.1016/j.cognition.2020.104418

Vallat, R. (2018). Pingouin: Statistics in Python. *Journal of Open Source Software*, *3*(31), Article 1026. https://doi.org/10.21105/joss.01026

Vroomen, J., & Keetels, M. (2010). Perception of intersensory synchrony: A tutorial review. *Attention, Perception, and Psychophysics*, *72*(4), 871–884. https://doi.org/10.3758/APP.72.4.871

Vul, E., Hanus, D., & Kanwisher, N. (2009). Attention as inference: Selection is probabilistic; responses are all-or-none samples. *Journal of Experimental Psychology: General*, *138*(4), 546–560. https://doi.org/10.1037/a0017352

Wearden, J. (2016). *The psychology of time perception*. Springer.

Whitney, D., & Levi, D. M. (2011). Visual crowding: A fundamental limit on conscious perception and object recognition. *Trends in Cognitive Sciences*, *15*(4), 160–168. https://doi.org/10.1016/j.tics.2011.02.005

Zelinsky, G. J. (2001). Eye movements during change detection: Implications for search constraints, memory limitations, and scanning strategies. *Perception and Psychophysics*, *63*(2), 209–225. https://doi.org/10.3758/BF03194463

Zelinsky, G. J., & Neider, M. B. (2008). An eye movement analysis of multiple object tracking in a realistic environment. *Visual Cognition*, *16*(5), 553–566. https://doi.org/10.1080/13506280802000752

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