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RESEARCH ARTICLE

Spatio-temporal contingency of saccade-induced chronostasis

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Abstract During fast, saccadic eye movements visual perception is suppressed. This saccadic suppression prevents erroneous and distracting motion percepts resulting from saccade induced retinal slip. Although saccadic suppression occurs over a substantial time interval around the saccade, there is no "perceptual gap" during saccades. The mechanisms underlying this temporal perceptual filling-in are unknown. When subjects are asked to perform temporal interval judgements of stimuli presented at the time of saccades, the time interval following the termination of the saccade appears longer than subsequent intervals of identical length. This illusion is known as "chronostasis", because a clock presented at the saccade target seemingly stops for a moment. We test whether chronostasis is a global mechanism that may compensate for the temporal gap associated with saccadic suppression. We show that a clock positioned halfway between the initial fixation point and the saccade target does not exhibit prolongation of the interval following the saccade. The characteristical distortion of temporal perception occurred only in the case of a clock being located at the saccade target. This result suggests a local, object-specific mechanism underlying the stopped clock illusion that might originate from a shift in attention immediately preceding the eye movement.

Introduction

From their personal experience, many people are familiar with the so-called "stopped clock" illusion. Observing a clock with a silently moving second hand, the second hand sometimes seems to take longer than just 1 s to move immediately after a saccade, depending on the timing of the eye movement relative to the second hand movement. The mechanisms underlying the perception of time are largely unknown (Buhusi and Meck 2005). A number of substantially different models of time perception have been proposed, ranging from a central internal clock to sensory timing (Allan 1979; Mauk and Buonomano 2004). Among several different illusions relating to perception of time (Rose and Summers 1995), the "stopped clock" phenomenon is one that relates to eye movements. No time misjudgement is observed when the eyes rest on the clock. Time misjudgements may occur while fixating, but they are different from the "stopped clock" illusion (Rose and Summers 1995; Tse et al. 2004).

The proposed mechanism underlying the "stopped clock" illusion has been named chronostasis (Yarrow et al. 2001). Chronostasis has been reported across different types of saccades (Yarrow et al. 2004b) and across a series of different stimulus durations (Yarrow et al. 2004a). Moreover, chronostasis-like phenomena can also be observed with other voluntary actions and sensory modalities such as key presses and voice commands (Park et al. 2003), voluntary arm movements and tactile stimuli (Yarrow and Rothwell 2003), and manual responses and auditory stimuli (Hodinott-Hill et al. 2002). In all these cases, the temporal intervals are defined at least partly by voluntary actions or their sensory consequences. Thus, saccades may cause a

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distortion in time perception in a similar manner to other voluntary actions. A general linkage between voluntary actions and the perceived timing of their sensory consequences might attract the two events so that they appear closer together in time (Haggard et al. 2002), although there are also explanations for distortions of perceived timing that are independent of motor acts (Hodinott-Hill et al. 2002; Alexander et al. 2005).

The objective of our experiments was to test the hypothesis of a global mechanism underlying the distortion of perceived timing in the original chronostasis experiment. Yarrow et al. proposed that chronostasis arises from a mechanism that compensates for the perceptually suppressed epoch during saccadic suppression. For this purpose, this mechanism should be global in a sense that it affects the complete visual field, image motion being suppressed not only in the center but also in the periphery (Ross et al. 2001).

Our experiment compares three different conditions of temporal duration judgements. Firstly, a fixation control condition in which a clock moved at saccadic speed towards the fixation point. Secondly, the original chronostasis condition in which a saccade was made towards the clock. These two conditions served as baseline for the third condition, the very condition we wanted to test. This third condition tested whether chronostasis is a global effect. Instead of presenting the clock at the saccade target, we presented it halfway between the fixation point and the saccade target.

Methods

Six subjects, four of them naïve to the aims of the experiment, and one an author, performed the experiment. All of them gave informed consent. The experiments have been carried out along the principles laid down in the declaration of Helsinki.

As outlined above, the first condition served as a baseline for temporal interval judgement in the absence of a saccade. Subjects fixated a small disc (diameter 1° visual angle), 8° to the left of the center of the screen, throughout the trial. The clock was presented 16° to the right of the fixation point, and initially consisted of a counter displaying the digit ‘0’, presented in about the same size as the fixation target. This counter moved with saccadic speed (about 330°/s, estimated from data of pilot experiments; monitor refresh rate was 144 Hz) towards the fixation point. A tone alerted the subjects to the impending movement of the clock stimulus. The stimulus movement began between 200 and 300 ms after the tone. When the counter reached the fixation point, it switched to ‘1’ and subsequently incremented up to ‘4’. The ‘1’ was visible for a random interval of 400–1,600 ms, the subsequent digits for 1,000 ms each without an inter-stimulus interval. After the last digit was displayed, the subject indicated whether the first interval appeared to be shorter or longer than the subsequent ones in a two-alternative forced-choice (2AFC). An experimental block comprised 100 trials. During the trials, eye position was continuously monitored (EyeLink I, SR Research, Inc., Canada). Trials in which the gaze position deviated from the fixation point more than 2° between the presentation of the tone and the beginning of the forth time interval were discarded. For analysis, we correlated the responses of each subject (First interval shorter or First interval longer) to the difference in duration between test stimulus (the ‘1’) and reference stimuli (subsequent digits). The durations of the test stimuli were uniformly distributed over the variation range. Hence, the data was binned regarding the presentation duration of the test stimulus. For each bin the proportion of trials in which the first interval appeared shorter was calculated. A cumulative gaussian curve was fitted to the data, the point of subjective equality (PSE) was evaluated by determining the duration at the interpolated 50% value of the curve.

In the two remaining conditions, subjects in addition to fixating the fixation point at the beginning of each trial, had to make a saccade to the target. In the original chronostasis condition, the counter was again visible 16° to the right of the fixation mark and initially consisted of the digit ‘0’. The counter also served as the saccade target. An acoustic cue signaled the beginning of a trial. The subject was free to conduct a voluntary saccade to the target anytime after the tone. Eye position was tracked online. When the eyes passed the horizontal center of the screen, the counter switched to ‘1’. This switch occurred approximately two-thirds through the saccade duration and varied slightly from trial to trial, whereby the ‘1’ then was visible for a random interval of about 300–1,700 ms from the time the eyes landed, estimated a priori, from the average latency of the eye tracking system, monitor refresh rate, and typical saccade duration. After the ‘1’ had disappeared, the counter progressed consecutively to ‘4’, with each digit being visible for 1,000 ms without an inter-stimulus interval. Due to saccadic suppression (Ross et al. 2001), it is unlikely that the counter change could be noticed by the subject during the saccade. We confirmed this in a separate suppression experiment described below. For a trial to be included in the data anaylsis, the post-saccadic eye position had to be within 5° from the saccade target, the counter switch had to be completed during the eye movement and fixation had to be maintained throughout the reference intervals. On average, 135 valid trials per subject and condition were included in this experiment. Since the number of accepted trials varied highly across subjects and experimental blocks, subjects did between two and six blocks each.

In the third condition, we presented the same stimuli and procedure as in the original chronostasis condition but the counter was located halfway between the fixation point (8° left) and the saccade target (8° right, same appearance as the fixation point). The counter initially showed a ‘0’. The subject had to execute a voluntary saccade from the initial fixation point to the target. As in the previous condition, the counter switched to ‘1’ when the eyes moved about two thirds of the distance and subsequently incremented up to ‘4’. The ‘1’ was visible for about 300–1,700 ms, the subsequent digits for 1,000 ms each. Timing and accuracy of eye movements were controlled offline. A simplified illustration of the screen presentation and experimental procedure is depicted in Fig. 1.

Results

The results of the baseline condition are shown in the first column (dark gray) of Fig. 2. There was a minor overestimation (median 75 ms) of the first interval if compared to the veridical duration. Thus, the point of subjective equality (PSE) was reached when the first interval was presented for 925 ms. This agrees in principle with results of Rose and Summers, who found an overestimation of the first stimulus in a sequential train of identical stimuli, although their effect was more pronounced.

The result of the original chronostasis condition with the counter at saccade target is shown in the second column (medium grey) of Fig. 2. Consistent with earlier reports (Yarrow et al. 2001), there was a distinct overestimation of the time interval immediately following the saccade, the median of this overestimation being 193 ms. Thus, the interpolated PSE is reached when the first interval following the saccade lasts for 807 ms. This value must be compared to the baseline condition, because there are already misestimations of time intervals during steady fixation. The difference between the median PSE in the saccade condition and in the baseline condition—the value that is referred to as chronostasis—is 118 ms and differs significantly from zero ($\alpha = 5\%$), tested with Fisher’s randomization test. The value is within the range of the results of earlier experiments (Yarrow et al. 2001, 2004a, b).

The results of the experimental condition with the counter halfway between fixation and target are shown in the third column (light grey) of Fig. 2. The median overestimation of the first interval was 82 ms, the corresponding PSE was 918 ms. This value was not significantly different from the baseline condition with no eye

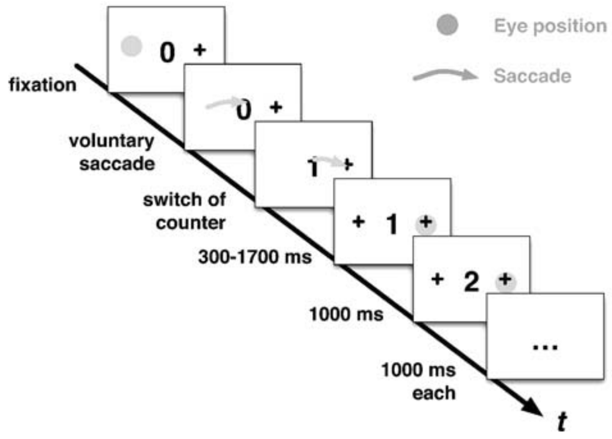

Fig. 1 Diagram of the screen presentations in the saccade condition with the counter intermediate between fixation point and saccade target. In the beginning the subject fixates the fixation point and the counter shows a ‘0’. After a tone occurs, the subject is free to saccade to the saccade target (amplitude 16°) when ready. While the eyes are moving, the counter changes to ‘1’. The ‘1’ is visible for about 300–1,700 ms from the time the eyes are landing, then the counter increments up to ‘4’, every subsequent digit visible for 1,000 ms with no inter-stimulus interval. After complete stimulus presentation a response screen containing two dots is displayed

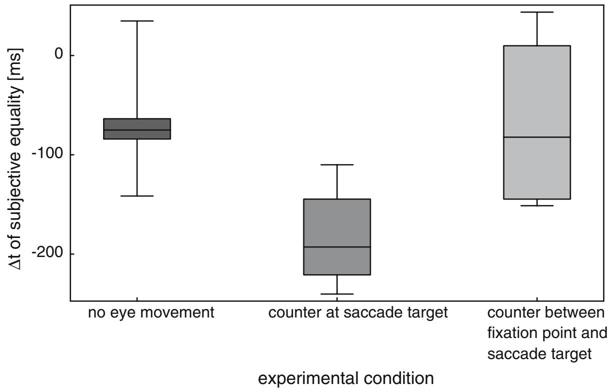

Fig. 2 Results of the three experimental conditions. *Dark grey* the baseline condition with the moving counter and no eye movement; *medium grey* the saccade condition with the counter as saccade target; *light grey* the saccade condition with the counter halfway between the fixation point and the saccade target. Data consists of the six subjects that participated in all three conditions. *Box-Whisker-Plots* show median, quartiles and variation range. The median in the saccade condition with the counter at saccade target is significantly ($\alpha = 5\%$) lower than in the other two conditions. There is no significant difference between the results of the baseline condition and the saccade condition with the intermediate counter position

movement, but was significantly different from the original chronostasis condition with the counter at the saccade target ($\alpha = 5\%$ with Fisher's randomization test).

Discussion

We therefore conclude that there is a distortion of perceived timing at the location of the saccade target but not at a location halfway between the initial fixation point and the saccade target. Accordingly, it is implausible that the distortion of perceived timing at the location of the saccade target is a global effect. Our results suggest a local effect, instead, presumably centered at or around the saccade target. If one takes into account that a potential mechanism compensating for saccadic suppression does not necessarily need to be global in the sense that it compensates for every detail of the visual world—because only a relatively sparse set of information is integrated transsaccadically—this local distortion of perceived timing as shown here might still suffice therefore.

A difference between the third experimental condition and the baseline condition is the location of the counter. In the baseline condition, as well as in the saccade condition with the counter at the saccade target, the duration of the first interval is judged when the counter is on the fovea. In the saccade condition with the counter halfway between fixation point and saccade target, the duration of the counter is judged 8° peripheral. However, it has been shown that the eccentricity of the counter does not influence the duration judgement systematically (Yarrow et al. 2001). In a control condition and a further control experiment—both described in their Experiment 1—they directly compare two conditions of duration judgement with a peripheral (22° and 55°) and a foveal counter, respectively, and found no significant differences.

The question is, why the time misjudgement is confined to the saccade target area. We believe that a combination of saccade-related attention shifting and a misperception of the time of saccade onset may explain our result. Spatial attention is known to be shifting mandatorily to the location of the saccade target just prior to a saccade (Peterson et al. 2004; Deubel and Schneider 1996; Irwin and Gordon 1998; Hoffman and Subramaniam 1995; Kowler et al. 1995). Furthermore, observers have been shown to misjudge the exact time of moving their eyes (Volkmann and Moore 1978; Deubel and Schneider 1996; Deubel et al. 1999). Volkmann and Moore (1978) found a substantial overestimation of the period the eyes are moving. While their results can be interpreted as revealing a general uncertainty of subjects about when there eyes actually move, Deubel et al. (1999) showed that, under some conditions, subjects judge events that occur before a saccade as occurring after it. They asked subjects whether a probe stimulus occurred before or after a voluntary saccade. Subjects judged the time of their saccade by about 145 ms too early if the test stimulus occurred at the location of the saccade target, presumably because attention shifted there before the saccade. However, in the case of the test stimulus occurring at the fixation point, the saccade onset was judged only 45 ms too early. Put differently, subjects reported that their gaze was already at the saccade target from 145 ms before saccade onset, and, in the second condition, reported that their gaze was at the fixation point up to 45 ms before the saccade. This reveals a difference of 100 ms in the perceived timing of saccade onset between the two probe locations.

Our hypothesis is based on the assumptions that, firstly, subjects misjudge the time of their eye movement and, secondly, subjects do not explicitly notice the counter change due to saccadic suppression. Saccadic suppression had to be confirmed for our experimental conditions. Therefore, two subjects participated in the additional suppression experiment. They had to detect a short, intra-saccadic counter switch. The experimental setup resembled very much the saccade condition with the counter at saccade target. The counter initially showed a '0', but switched to a '1' in 50% of the trials (pseudo-randomized) during the saccade. After one monitor frame (7 ms), it switched back to '0'. When the eyes were landing, a '0' was visible in every trial. The subjects were asked to indicate if they had noticed a counter switch during the saccade in a two-alternative forced-choice. Mean detection rate for the two subjects was 9.7% (6.4 and 13.0%, respectively), false alarm rate 2.8% (1.9 and 3.7%). We thus conclude that the intra-saccadic counter switch is not noticed.

In our chronostasis condition, subjects cannot notice the first change of the counter during their eye movement because of saccadic suppression. Therefore, they have no explicit perception of the onset of the test interval. Subjects may correctly interpret this onset as having occurred during the saccade and before their gaze reached the counter. As subjects perceive their gaze to be at the saccade target well before the saccade, the onset of the test interval would also be misjudged as too early, if the stimulus defining the interval is presented at the saccade location. For a clock at the fixation position or at an intermediate position, the onset of the test interval should be perceived more correcly because the onset of gaze shift is perceived more correctly. The differences found between the onset judgements of stimuli presented at saccade target and fixation point (Deubel et al. 1999) quantitatively matches the differences in perceived timing in our data.

Attentional explanations for our results could include a contribution of inhibition of return. We may speculate that the task-relevant counter likely attracts attention in the beginning of the trial. Shortly before the saccade, attention must be shifted to the future saccade target (Hoffman and Subramaniam 1995; Kowler et al. 1995; Deubel and Schneider 1996; Peterson et al. 2004). Therefore, inhibition of return may occur at the counter location, i.e. the previous locus of attention, and may contribute to a delayed processing of visual information from that location. Whether or not this is the case, however, cannot be concluded from the present experiments.

Yarrow et al. argued against an involvement of attention, because chronostasis occurred also in a control condition in which subjects had to voluntarily shift their attention to the saccade target some time prior to the saccade. However, it is possible that, even if explicit attention is shifted to the saccade target early on, implicit attentional ressources are recruited around saccade onset, as the association between eye movements and attention shifts is not consciously detachable (Peterson et al. 2004; Hoffman and Subramaniam 1995; Kowler et al. 1995).

Morrone et al. (2005) recently provided evidence of an effect different to the distortion of perceived timing described above. Their test intervals were only 100 ms long, involving the discrimination of temporal intervals between two flashing stimuli around saccade onset. They found a pronounced compression of temporal perception around the time of saccades, accompanied by a perceived inversion of temporal order. This compression of time has approximately the same time course as the saccadic compression of space, from shortly before to shortly after the saccade, reaching its maximum at the beginning of the saccade. Furthermore, this effect seems to be global, insofar as Morrone et al. (2005) used peripheral stimuli that covered the whole monitor width, as well as smaller stimuli closer to the saccade target. Note that in their experiments subjects do not necessarily need knowledge about their actual or subjectively perceived gaze position over time to solve the tasks. Because of both, its different time course—maximal at saccade onset and swiftly diminishing toward saccade end—and its global effect, we think that the compression of perceived timing is caused by a mechanism different from chronostasis. Unlike this compression of perceived timing we showed chronostasis to be a local, and presumably attention-related, phenomenon.

References

Alexander I, Thilo KV, Cowey A, Walsh V (2005) Chronostasis without voluntary action. Exp Brain Res 161:125–132

Allan LG (1979) The perception of time. Percept Psychophys 26:340–344

Buhusi CV, Meck WH (2005) What makes us tick? Functional and neural mechanisms of interval timing. Nat Rev Neurosci 6:755–765

Deubel H, Schneider WX (1996) Saccade target selection and object recognition: evidence for a common attentional mechanism. Vision Res 36:1827–1837

Deubel H, Irwin DE, Schneider WX (1999) The subjective direction of gaze shifts long before the saccade. In: Becker W, Deubel H, Mergner T (eds) Current oculomotor research: physiological and psychological aspects. Plenum, New York pp 65–70

Haggard P, Clark S, Kalogeras J (2002) Voluntary action and conscious awareness. Nat Neurosci 5:382–385

Hodinott-Hill I, Thilo KV, Cowey A, Walsh V (2002) Auditory chronostasis: hanging on the telephone. Curr Biol 12:1779–1781

Hoffman JE, Subramaniam B (1995) The role of visual attention in saccadic eye movements. Percept Psychophys 57:787–795

Irwin DE, Gordon RD (1998) Eye movements, attention and trans-saccadic memory. Vis Cogn 5:127–155

Kowler E, Anderson E, Dosher B, Blaser E (1995) The role of attention in the programming of saccades. Vis Res 35:1897–1916

Mauk MD, Buonomano DV (2004) The neural basis of temporal processing. Annu Rev Neurosci 27:307–340

Morrone MC, Ross J, Burr D (2005) Saccadic eye movements cause compression of time as well as space. Nat Neurosci 8:950–954

Park J, Schlag-Rey M, Schlag J (2003) Voluntary action expands perceived duration of its sensory consequence. Exp Brain Res 149:527–529

Peterson MS, Kramer AF, Irwin DE (2004) Covert shifts of attention precede involuntary eye movements. Percept Psychophys 66:398–405

Rose D, Summers J (1995) Duration illusions in a train of visual stimuli. Perception 24:1177–1187

Ross J, Morrone MC, Goldberg ME, Burr DC (2001) Changes in visual perception at the time of saccades. Trends Neurosci 24:113–121

Tse PU, Intriligator J, Rivest J, Cavanagh P (2004) Attention and the subjective expansion of time. Percept Psychophys 66:1171–1189

Volkmann FC, Moore RK (1978) Saccadic eye movements and the perception of a clear and continuous vusual world. In: Armington JC (ed) Visual psychophysics and physiology. Academic, London, pp 353–362

Yarrow K, Rothwell JC (2003) Manual chronostasis: tactile perception precedes physical contact. Curr Biol 13:1134–1139

Yarrow K, Haggard P, Heal R, Brown P, Rothwell JC (2001) Illusory perceptions of space and time preserve cross-saccadic perceptual continuity. Nature 414:302–305

Yarrow K, Haggard P, Rothwell JC (2004a) Action, arousal, and subjective time. Conscious Cogn 13:373–390

Yarrow K, Johnson H, Haggard P, Rothwell JC (2004b) Consistent chronostasis effects across saccade categories imply a subcortical efferent trigger. J Cogn Neurosci 16:839–847