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Illusory perceptions of space and time preserve cross-saccadic perceptual continuity

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When voluntary saccadic eye movements are made to a silently ticking clock, observers sometimes think that the second hand takes longer than normal to move to its next position¹. For a short period, the clock appears to have stopped (chronostasis). Here we show that the illusion occurs because the brain extends the percept of the saccadic target backwards in time to just before the onset of the saccade. This occurs every time we move the eyes but it is only perceived when an external time reference alerts us to the phenomenon. The illusion does not appear to depend on the shift of spatial attention that accompanies the saccade. However, if the target is moved unpredictably during the saccade, breaking perception of the target's spatial continuity, then the illusion disappears. We suggest that temporal extension of the target's percept is one of the mechanisms that “fill in” the perceptual “gap” during saccadic suppression. The effect is critically linked to perceptual mechanisms that identify a target's spatial stability.

Although most observers have experienced the “stopped clock” illusion, previous psychophysical experiments that have tested when subjects perceive the time of transient external events relative to saccadic eye movements have yielded contradictory results^{2,3}. A possible reason for this is that the saccade itself causes changes in temporal perception at around the time of eye movement. We tested whether the perceived duration of chronostasis is affected by the duration of the saccade. Subjects made saccades of either 22 or 55 degrees (lasting on average 72 and 139 ms respectively) to a numerical counter. The movement of the eyes was used to start the counter incrementing once every second, with the exception that the duration of the first number could be varied between 400 and 1600 ms. Subjects had to say whether the time they had seen the first digit was more or less than that for the subsequent digits (a constant 1 s). Figure 1 shows that subjects thought they had seen the initial digit for 1 s when their gaze had been on the target for only 880 ms (22° saccade) or 811 ms (55° saccade). Control trials in which the same temporal judgement was made either without moving the eyes, or if the target rather than the eye saccaded into the visual field, gave significantly different values that were very close to the “correct” value of 1 s. Interestingly, there was an almost exact agreement between the extra time taken for the eyes to move over the longer distance ($139-72 = 67$ ms) and the difference in the time intervals that subjects matched to 1 s ($880-811 = 69$ ms), suggesting that the illusion of chronostasis is linked to the time taken to move the eyes. In fact, subjects appeared to extend the time that they thought they had seen the first target back in time to approximately 50 ms prior to the start of eye movement. Although subjects reported no awareness of the counter changing during their saccades, it is possible that they were able to use this digit shift as a cue to initiate time judgements. This would invalidate the matched times we calculated (measured from the moment the eyes actually reached the counter). However, a control experiment in which the counter was triggered either very early or very late during a large (55°) saccade showed no difference in the duration of chronostasis, despite modifying the period that the digit was actually on screen by 85 ms.

The tight coupling of the duration of chronostasis to the duration of the saccade suggests that the effect may be linked to the perceptual “gap” caused by saccadic suppression and retinal blur that occurs when we move the eyes^{3, 4}. However, it is possible that the illusion of chronostasis is not tightly coupled to movement of the eyes per se, but occurs because subjects also shift the locus of their visual attention at around the time their eyes move⁵. This attention shift may act as the reference point to which the target is predated. In order to test this, subjects were asked either to make the usual saccade to target or first to shift their attention to the target and then move their eyes. Figure 2a shows that the illusion of chronostasis persisted with a similar magnitude when subjects shifted their attention before moving their eyes. Control trials intermixed with the eye movement trials verified that subjects were successful in shifting the locus of their visual attention⁶. They fixated a central cross and had to saccade to a target appearing on the right or left of the screen. If they had been told to shift their attention to the correct side before the target appeared, their reaction time was faster than if they had been incorrectly cued (Fig 2b).

Although chronostasis is linked to voluntary saccades, the coupling is not obligatory: there is at least one condition under which the illusion is not experienced. We designed a third experiment in which the positional stability of the target counter was systematically broken. Subjects made a saccade to target, but in some trials the computer displaced the target by up to 9 degrees during the time the eyes were moving. Under such conditions, subjects sometimes fail to notice the shift and make an unusually large corrective saccade to fixate the target^{7, 8}. Trials were divided into three types: (1) those in which the counter remained stationary throughout, (2) those in which it was moved but the movement was not perceived by the subject, and (3) trials in which target movement was perceived by the subjects. Figure 3 shows the results of this experiment. When there was no target motion, subjects experienced the usual illusion of chronostasis when they made a saccade compared with a control condition with no movement of the eyes. However, if the target was moved and subjects noticed the movement, then no effect was found relative to control. If the shift was not perceived, subjects’ estimates fell between the

control value and the full illusory effect. The effect of moving the target was not due to non-specific distraction caused by the shift. The full illusion was again obtained in our final experiment, in which distracting stimuli appeared randomly 1 or 3 degrees to the side of the target during the time the eyes were moving and remained on the screen thereafter (fig 3).

Thus backwards extension of the target's percept only occurs when subjects perceive that the saccadic target was stationary during the period of extension. We suggest that this link between space and time occurs because of the following. When the saccade shifts the eyes from one stationary viewpoint to another, vision is degraded and it is not possible to say with certainty whether there are any changes in the position of objects during movement. However, if the saccadic target is fixated accurately at the end of the saccade, subjects can assume that it occupied approximately the same place throughout the eye movement (*object constancy*). Such an assumption may fulfil various functions, having already been proposed in recent theories relating to the problem of space constancy⁹⁻¹¹. Since there is no other competing percept (because vision is blurred during the saccade), the assumption of a constant target position is linked to an extended temporal perception of the object as seen at the end of the saccade. If the target jumps, then object constancy is broken, and chronostasis fails to occur. Conscious awareness of a target jump may be linked to the assumption of object constancy, but is unlikely to mirror it precisely. This may explain the partial (non-significant) effect for targets that shift without the subject becoming aware of this change.

It was interesting that the target percept, rather than being extended back to the time of saccadic onset, predates this by up to 120 ms. Although predating of the target's post-saccadic state to a specific pre-motor event (such as the efferent command) is one possibility, it is noteworthy that the processes underlying both saccadic suppression and space constancy are active over a time period extending beyond the saccade itself⁴. Our obtained constant values are similar to the value of 80 ms obtained for pre-saccadic shifts in neuron receptive fields within the lateral intraparietal area of monkeys¹². They also fit well with human psychophysical data on

pre-saccadic compression of space (the systematic mislocalisation of targets flashed around the time of a saccade) and saccadic suppression, which both precede saccadic onset by 50ms or more^{13, 14}. It therefore seems very likely that pre-saccadic mechanisms will provide an explanation for the time course of chronostasis.

These data support notions of conscious experience as an ongoing, often post-hoc reconstruction emerging from multiple cognitive systems¹⁵⁻²¹. Our suggestions relating to assumed continuity of target appearance fit well with notions about object files current in the visual attention literature^{22, 23}. Here, features of a visual object (colour, form, location etc.) are bound into a single perceptual unit (the object file) that links representational codes established across diverse cortical regions. We suggest that cross-saccadic perceptual continuity, as described here, may represent a specific case of a more general class of phenomena relating to the continuity of perception across shifting states of sensory input.

Methods

Subjects sat before a 14" colour monitor (60 Hz refresh), chin supported. Eye movements were recorded using electro-oculography or with an infrared eye tracker (Microguide 1000 spectacles) and sampled at 200 Hz. Stimuli were black on a white background or vice versa, subtending approximately 0.5°. The experiments were controlled by a PC interfaced with a 12 bit A/D card (National Instruments DAQ 1200). Counter change was triggered when the eyes had travelled 1/5th of the distance to target. Saccade start/end points were calculated automatically using a velocity criterion. Repeated measures designs were used throughout, with condition order counterbalanced. N for each experiment was calculated following a power analysis of initial data sets. Later experiments replicate experiment 1 unless otherwise stated.

Experiment 1. 30 subjects (18 male, mean age 28.2, SD 7.4) completed four conditions: Saccades of 55° and 22° and two matched control conditions. In the saccade

conditions, subjects fixated a cross on one side of the screen, initiated the trial with a key press then made a voluntary saccade to a target “0” on the other side. Eye movement triggered a change of digit to a “1”, which remained on screen for 400-1600ms; subsequent digits (“2”, “3”) remained on the screen for 1 s each, culminating in the appearance of a “4”. Subjects indicated whether the time they saw the “1” was longer or shorter than that for the subsequent digits. Trials where the first saccade recorded did not exceed 90% of the total distance to target were excluded on line. In control trials, subjects fixated a “0” at equivalent eccentricity that changed to become the judged digit (“1”) 500 ms after the subject’s key press. The computer controlled the duration of the first digit by a modified binary search (MOBS)²⁴ procedure that “homed in” on a single matched estimate (low boundary 400 ms, high boundary 1600 ms, initial presentation random 800-1200 ms, 5 reversals to terminate). Four estimates were obtained per condition, then corrected post hoc to match the time the “1” was on screen *following target foveation*.

10 subjects (9 male, mean age 30.5, SD 7.8) completed a control experiment. They estimated first digit duration when a counter moved 24° to the point of fixation in 100 ms (6 screen refreshes), compared to the usual stationary control. A further control experiment (N = 10, 9 male, mean age 31.4, SD 7.6) varied the time from saccade onset to the initial counter change by triggering this change either 1/5th or 4/5th of the way into a 55° saccade (randomly within the same block; separate self-terminating MOBS).

Experiment 2. 12 subjects’ data were included in experiment 2 (10 male, mean age 32.8, SD 9.3). In addition to a control, subjects completed two conditions requiring 12° saccades to a counter (as experiment 1) *with or without deliberate prior covert shifting of attention*. Every other trial was a reaction time task in which subjects fixated the central target then made a speeded 12° saccade to the appearance of a target “0” to the

left or right. An uninformative cue (an arrow pointing to the left or right near fixation) directed attention prior to the appearance of the “0” in attention-shift blocks.

Experiment 3. 22 subjects performed experiment 3 (16 male, mean age 30.8, SD 7.4). Three conditions were tested: a 20° saccade to a stationary counter, a 20° saccade in which the counter shifted $\pm 0-9^\circ$ synchronous with counter onset triggering, and a control. All eye movement data were obtained within a single block type, in which subjects made the standard timing judgment and also indicated whether the counter had moved during the saccade. Presentation was controlled by three randomly interleaved (equally probable) self-terminating MOBS. The first controlled target time intervals for the stationary counter trials (as exp. 1), the latter two controlled the size of the target shift in a hypo- or hyper-metric direction (0-9°) according to whether the movement was perceived. This ensured that the majority of shift trials were close to the subject’s point of shift perception, whether perceived or not. For shift trials, the target time interval was randomly generated in the range 400-1600 ms. Trials were divided between perceived and unperceived shift conditions post hoc. For all conditions, matched time estimates were generated using logistic regression. Subjects initially completed four experimental blocks and four short control blocks, with a single additional block completed where fitted logistic regression lines exceeded $p = 0.05$.

Experiment 4. 10 subjects participated (7 male, mean age 29.4, SD 7.5). Four conditions were compared: A 20° saccade to a stationary counter, an identical saccade with a random lower case alphabetic character appearing 1° from the counter (hypo- or hyper-metrically) at trigger time, a saccade with the character appearing 3° from the counter, and a control. Data for the first three conditions was obtained within a single block type, using three randomly interleaved and self-terminating MOBS.

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Figure 1. Results of experiment 1. Error bars show standard deviations. **A.** Schematic of experimental method. **B.** Mean time (ms) matched to one second for two conditions involving saccades of 55° and 22° and two control conditions (without saccades) at matched eccentricities. Chronostasis occurs in both experimental conditions compared to controls ($t[29] = 9.612$, $p < 0.001$, $t[29] = 5.608$, $p < 0.001$) and increases linearly in one-to-one correspondence with saccade duration ($t[29] = 2.553$, $p < 0.05$). **C.** Results for a control experiment where the counter moves to the point of fixation. Chronostasis is not obtained. **D.** Results for a comparison between the standard saccade-to-counter-onset interval and a much longer interval. The duration of chronostasis is unaffected.

Figure 2. Results for experiment 2. Error bars show standard deviations. **A.** Mean time (ms) matched to one second for two conditions involving saccades with/without early deliberate reorienting of attention and a control condition. Shifts of attention cannot account for chronostasis because covertly shifting attention early on does not influence the effect size. The low subjective seconds appear to differ from the saccade-duration-related results of experiment 1 (figure 1) for a shorter (12°) saccade. However, inter-subject variability is high for this task; when data for only those 9 subjects who participated in both studies is considered, the results continue to support a linear effect size scaling with saccade duration. **B.** Mean RT (ms) for a two-choice saccade task with no attention directing cue, a correct cue or an incorrect cue. Subjects succeeded in reorienting attention, as confirmed by the significantly lower RT for the correct cue and no attention conditions relative to the incorrect cue condition ($t[11] = 4.108, p < 0.01$; $t[11] = 5.367, p < 0.001$). Error data (not shown) displayed a similar pattern.

Figure 3. Results for experiments 3 and 4. Error bars show standard deviations. **A.** Schematic of a shift trial (exp. 4). **B.** Mean time (ms) matched to one second for four conditions: Standard saccade (20°), saccade with detected counter displacement ($\pm 0-9^\circ$), saccade with undetected counter displacement ($\pm 0-9^\circ$) and control. Chronostasis (standard saccade $t[21] = 4.283$, Bonferroni $p < 0.01$) is eliminated when saccade target stability is noticeably violated and moderated when such a violation goes unnoticed. **C.** Mean time matched to one second (ms) for four conditions: Standard saccade (20°), saccade with appearance of a distracter 1° from the target, saccade with appearance of a distracter 3° from the target, and control. Chronostasis is obtained regardless of the distracter ($t =$

3.500, Bonferroni $p < 0.05$; $t = 3.220$, Bonferroni $p = 0.063$; $t = 3.724$, Bonferroni $p < 0.05$).

Figure 1

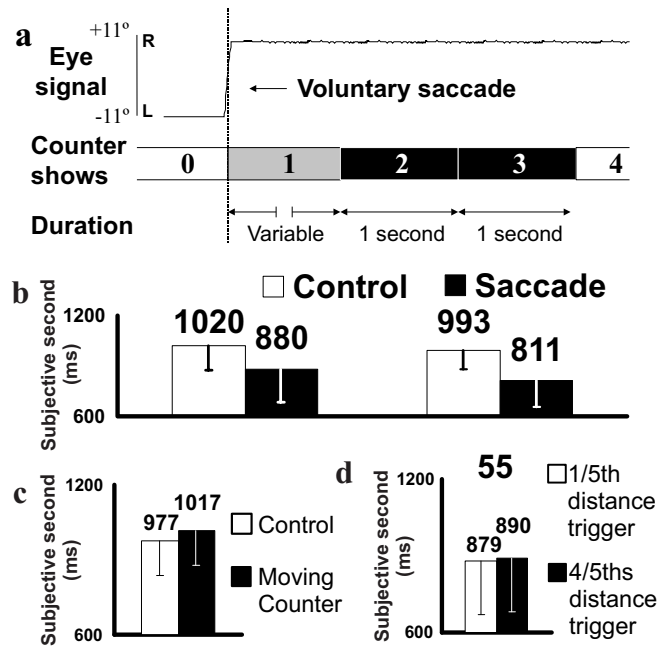


Figure 2

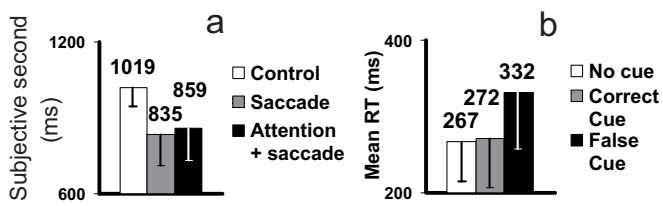


Figure 3

