

Saccadic chronostasis and the continuity of subjective temporal experience across eye movements

Kielan Yarrow^{1*}, Patrick Haggard^{2,3} & John C Rothwell⁴

1. Department of Psychology,
City University

2. Institute of Cognitive Neuroscience,
U.C.L.

3. Department of Psychology,
U.C.L.

4. Sobell Department of Motor Neuroscience and movement disorders,
Institute of Neurology,
U.C.L.

* Author for correspondence:

Kielan Yarrow,
Social Science Building,
City University,
Northampton Square,
London EC1V 0HB

Tel: +44 (0)20 7040 8530

Fax: +44 (0)20 7040 8580

Email : kielan.yarrow.1@city.ac.uk

Abstract

The term saccadic chronostasis refers to the subjective temporal lengthening of a visual stimulus perceived following a saccadic eye movement. In this paper, we discuss our preferred account of the illusion, which posits that the onset of the post-saccadic stimulus is antedated to a moment just prior to movement initiation, and review supporting evidence that illustrates some key characteristics of the illusion, including its dependency on saccade extent. We conclude with a brief discussion of other examples of biased time perception that have been linked to saccadic chronostasis.

10.1. Introduction

When people make a saccadic eye movement to fixate a new visual target, they overestimate the duration for which that target is perceived (Yarrow, Haggard, Heal, Brown & Rothwell, 2001). This illusion, which we have called saccadic chronostasis, has been demonstrated using the following basic procedure. Subjects make a saccade to a target that changes form or colour during the saccade. They judge the duration of the new target stimulus relative to subsequently presented reference stimuli, and these judgements are used to determine a point of subjective equality (PSE; the point at which the target and reference stimuli are perceived to have identical durations). This procedure is schematised in Figure 10.1. The same task performed while fixating forms a control. Reduced PSEs in saccadic compared to control fixation conditions are a gauge of the temporal overestimation of the post-saccadic stimulus.

INSERT FIGURE 10.1 AROUND HERE

A similar effect can also be observed in a more everyday setting. The “stopped clock” illusion occurs when upon glancing at a watch with a moving second hand we think, just for a moment, that it has stopped working. This experience is one that many people recognise, and prompted the first investigations of saccadic chronostasis. It does not occur every time we look at our watch, but only on those occasions when the watch hand (or a digital counter) changes just before or during the saccade (Brown & Rothwell, 1997). In these cases, the next interval seems to exceed the prescribed duration of one second.

Aside from explaining this common perceptual experience, why study saccadic chronostasis? In this paper, we propose that the illusion helps explain how our visual experience consists of a seamless progression of fixations without any intervening saccadic gaps. In elucidating this account, our approach will be as follows. First, we will describe a number of key findings from the various saccadic chronostasis experiments we have conducted to date, followed in each case by our interpretation of them. Next, we will discuss some methodological points that bear on the interpretation of saccadic chronostasis experiments. Finally, we will briefly discuss some other biases in temporal perception that have been linked to saccadic chronostasis and assess commonalities and distinguishing features.

10.2 Key experimental results supporting the antedating account

10.2.1 Saccadic chronostasis is greater for longer saccades than for shorter saccades

Using the basic methodology described above, Yarrow et al. (2001) found that subjects did indeed overestimate the duration of a stimulus they had just fixated with a rapid eye movement. Subjects made saccades of either 22° or 55° extent and judged the duration of a post-saccadic stimulus. They made the same judgement in two control conditions involving fixation at an identical orbital eccentricity. The size of the resultant bias was found to depend upon the duration of the saccade. The bias was greater in the large saccade condition than in the small saccade condition, and this difference was comparable to the difference in saccadic duration. We will refer to this as the *saccade length effect*.

This finding is consistent with the hypothesis that the timeline of events recalled following a saccade is non veridical. Observers do not report a duration that is consistent with having perceived the post-saccadic stimulus at the moment it was foveated (the end of the saccade) or even at the moment it first appeared (during the saccade). Instead, they report a duration that is consistent with having seen this stimulus approximately 50 ms *before* they moved their eyes. We refer to this as the *antedating* hypothesis. Note that antedating might result from either prospective or retrospective processes. It is possible that a clock process is automatically initiated before the onset of each saccade (a prospective account). On the other hand, events occurring around the time of the saccade could be retrospectively interpreted before a judgement about duration is made. In sections 10.2.4 and 10.2.5 we will make a tentative case suggesting that timing processes are initiated prospectively, but that the reported experience reflects a combination of this

prospective time estimate with detailed visual information that is available only in retrospect.

There are a number of other observations that can inform, or be interpreted within, the antedating framework. During a saccade, visual input is highly degraded. High spatial frequency visual information is smeared by the rapid movement of the eye, while low spatial frequency visual information is subjected to an active process of saccadic suppression (Ross, Morrone, Goldberg & Burr, 2001). The visual input is further suppressed as a result of backwards masking by the post-saccadic image (Campbell & Wurtz, 1978). These results explain our failure to perceive motion during a saccade, but not our failure to experience any interruption of normal vision during this interval. The recollection of a timeline of events that effectively eliminates the saccade seems to provide the final piece in this puzzle, explaining the complete lack of visual experience during the period our eyes are in motion.

10.2.2 Stimulus duration does not influence the magnitude of saccadic chronostasis

In two experiments, Yarrow, Haggard and Rothwell (2004) selected a range of reference durations between 100 ms and 1333ms, and then determined the PSE for a post-saccadic stimulus for each of them. They found that the size of the saccadic chronostasis effect was constant and independent of stimulus duration.

We were motivated to run these experiments because while the saccade length effect is consistent with the antedating hypothesis, it is not conclusive on its own. Problems of interpretation arise because the measure that is being used (the perceived

duration of the post-saccadic stimulus) cannot be unambiguously related to the perceptual event about which we are making a claim (the onset of the post-saccadic target). In physics, the duration of an interval can only be changed by adjusting the time when the events that border that interval occur. Psychologically, however, this is not the case: Perceived duration can be affected by a number of non-temporal factors (Allan, 1979). Many theorists relate these changes in perceived time to the rate at which some hypothetical internal clock is functioning (Treisman, Faulkner, Naish & Brogan, 1990; Wearden, Edwards, Fakhri & Percival, 1998). Hence our earlier results could reflect a change in clock rate rather than temporal antedating (Hodinott-Hill, Thilo, Cowey & Walsh, 2002).

If saccadic chronostasis is the result of a change in clock rate, the size of the effect should depend on the duration of the post-saccadic interval that is being judged. This follows because subjective time will equal objective time multiplied by clock rate. This prediction was not verified. However, this result does not conclusively rule out an account based upon a change in clock rate, if we accept that such a change might be extremely transient i.e., already complete by the time the shortest duration stimulus that was tested had terminated. Hence the data obtained merely constrain a clock rate account, implying an increase that is both dramatic and brief.

10.2.3 The subjective time of onset for a post-saccadic stimulus is much earlier than for the same stimulus judged at fixation

Yarrow, Whiteley, Haggard & Rothwell (2006) carried out a typical saccadic chronostasis experiment in which subjects made saccades of either 10° or 50° extent. The same subjects also completed an experiment in which a brief auditory stimulus (a beep) sounded around the time they moved their eyes. In this case, their task was to judge whether the auditory stimulus came on before or after they first saw the post-saccadic visual stimulus (i.e., a cross-modal temporal order judgement). A large bias emerged in both experiments. In the standard chronostasis experiment, the post-saccadic stimulus had an extended subjective duration compared to control conditions. In the temporal order judgement experiment, the beep had to be sounded before the post-saccadic target was foveated in order to be perceived as synchronous with it. Importantly, this bias was assessed relative to a control condition without an eye movement, to take account of the latency differences between the visual and auditory modalities.

These experiments provide more direct evidence supporting the antedating account. In both experiments, effects were larger following large saccades than following small saccades. Hence, two completely different tasks applied to the same experimental situation provided consistent evidence that the perceived time of onset for the post-saccadic stimulus was earlier than both the moment it was foveated and its physical onset on the screen. The temporal order judgement task is explicitly an event judgement task. It therefore circumvents the problem of measuring the chronostasis effect previously using interval judgements as an implicit index of subjective events.

2.4. Saccadic chronostasis is eliminated when the saccade target jumps during a saccade

Yarrow et al. (2001) found that saccadic chronostasis did not occur when the saccade target was noticeably displaced (i.e., jumped horizontally by around 3°) at the same time it changed form during the saccade. The saccadic chronostasis effect returned partially when the same displacement went unnoticed, and was observed as usual when distracters appeared close to the saccade target during the saccade. More recent unpublished work suggests that a second object in the post-saccadic display other than the saccade target can be subject to saccadic chronostasis when participants judge its duration. Just as for the saccade target object, displacement of this second object also eliminates saccadic chronostasis when this object is being judged.

Antedating might be implemented in a prospective or retrospective fashion. In non-laboratory settings, the stopped clock illusion is frequently experienced despite the fact that the post-saccadic target is both unpredictable and available only to peripheral vision prior to the saccade. This would seem to preclude a detailed real-time percept at the time of the target's perceived (pre-saccadic) onset, and favour a retrospective account. However, the timing mechanism might still be prospective, with the subsequent detailed percept being retrospectively anchored to a moment determined in real time. Of course, anecdotal reports of the stopped clock illusion lack proper experimental control. In the lab the post-saccadic target is highly predictable, so anticipation can contribute to peri-saccadic perception, implying that both timing processes and conscious perception might be determined prospectively.

The fact that chronostasis disappears when the saccade target jumps seems to imply a retrospective interpretative process, because perception changes depending upon an event that occurs only after the target is reported to be seen. High-level processes such

as these are appropriate when sensory input is degraded or ambiguous, and may depend upon prior expectations (e.g. Yang & Purves, 2003). For peri-saccadic vision, one reasonable expectation is that the world has not changed a great deal during the period of the saccade. When we designed our experiments with a jumping target, we predicted that perception would be modulated when sensory evidence is available that contradicts the expectation of peri-saccadic continuity. The target's jump may violate expectations about the stability of the external world across eye movements and therefore veto a default tendency to antedate the post-saccadic stimulus.

Our experiments reveal the timeline of events that subjects recall across a saccade, but a question remains about exactly what they believe they have actually seen in the saccadic interval. We have recently begun to address this issue. We observed chronostasis following saccades to a moving object, but our subjects did not perceive a corresponding period of stimulus motion filling the saccadic gap (Yarrow, Whiteley, Rothwell & Haggard, 2006). Their percept was inferred based upon the first position at which they reported seeing the post-saccadic target, which was actually ahead of its true position, not behind it (although slightly less ahead of its true position than a similar target judged without a prior saccade). It appears then, that our perception of the timing of events can be adjusted without requiring a complementary adjustment to spatial vision; an example of how different stimulus properties can become dissociated in conscious perception.

10.2.5 Saccadic chronostasis is obtained equally for different kinds of saccades

In two experiments, Yarrow, Johnson, Haggard & Rothwell (2004) found that the saccadic chronostasis effect could be obtained with a similar magnitude for many different kinds of saccades, including self timed saccades, pro- and anti-saccades, and even express saccades.

These experiments offer some insight into the possible neural locus of the effect. An extensive network of brain areas is involved in the production of saccades, but express saccades (those elicited in a gap paradigm with a latency of 70-130 ms; Fischer & Ramsperger, 1984) are generally held to be generated in exclusively sub-cortical regions (Hopp & Fuchs, 2002). The antedating hypothesis predicts that an efference copy signal relating to the saccade must be transmitted to brain regions that can determine when the post-saccadic stimulus appeared, and how long it was presented for. The finding of saccadic chronostasis following express saccades suggests that this signal may originate in the superior colliculus. We also found that chronostasis occurs with a similar magnitude for pro- and anti-saccades, where action planning processes differ markedly. This finding also suggests that a late efference copy signal is critical; motor preparation takes longer, and therefore starts earlier for anti-saccades compared to pro-saccades, but this early activity does not give rise to a larger chronostasis effect.

While a subcortical signal may *trigger* chronostasis, and directly initiate certain timing operations, any retrospective adjustment of perceptual content is presumably generated elsewhere. So where is this signal transmitted to? We have speculated that the experience of saccadic chronostasis may reflect receptive field shifts of visual neurones. These were first described in the lateral intra-parietal area (LIP) of behaving monkeys (Duhamel, Colby & Goldberg, 1992) and have been found more recently in a number of

other brain areas (Nakamura & Colby, 2002; Umeno & Goldberg, 1997; Walker, Fitzgibbon & Goldberg, 1995). Some apparently retino-centric cells in these areas begin to respond *before a saccade has been initiated* to stimuli at locations that the saccade will bring into their receptive fields. The timing of this pre-saccadic activity varies widely across cells, but a brain region capable of averaging these neurones' initial responses to a post-saccadic stimulus could contribute to the experience reported during saccadic chronostasis experiments. While the idea that receptive fields shift in response to an efference copy signal from the superior colliculus is physiologically plausible (Sommer & Wurtz, 2002), the part played by such cells in producing saccadic chronostasis remains hypothetical.

10.3 Methodological issues.

10.3.1 Is saccadic chronostasis simply an order effect?

When two or more intervals are presented in sequence, participants often exhibit biases in their temporal judgements. The best known example is the time order error (see Hellstroem, 1985, and Allan, 1979, for reviews). Subjects' judgements are often biased such that two identical consecutively presented intervals do not appear of equal duration. Either interval can appear prolonged, and the direction and magnitude of the bias is difficult to predict. There are also other examples of specific biases arising as a result of sequential presentation of stimuli. Rose & Summers (1995) reported that when four squares are presented with intervening blank periods, the first and the fourth square seem

prolonged compared to the middle two. It is also possible to observe the influence of one interval on another when one of these intervals is evaluated with a comparison stimulus that is presented much later (e.g. Sasaki et al., 2002). However though others have suggested that chronostasis is caused by the same mechanism as sequence effects (Hunt, Chapman & Kingstone, 2008), none of these biases are directly relevant to saccadic chronostasis. Chronostasis is always evaluated relative to a control condition with identical sequential properties. Demonstrations of saccadic chronostasis, therefore, reveal a bias in subjective duration *over and above* any order effects that may be present in the particular procedure employed.

10.3.2 Do constant fixation conditions provide a suitable control?

The purpose of the constant fixation conditions in saccadic chronostasis experiments is to provide a match for the pattern of visual stimulation experienced in saccadic conditions. Three different kinds of control condition have been used. The first type matches sequence effects (see above) but provides only an approximate match for visual stimulation. For example, Yarrow et al. (2001) and Park, Schlag-Rey & Schlag (2003) used a numeric counter (“0”, “1”, “2”, “3”, “4”) in fixation conditions (judge the “1”, relative to the “2” and the “3”). In saccade conditions, subjects fixated a cross, then saccaded to the same counter, which changed to display a “1” mid-saccade then progressed through the same numerical sequence. Hence foveal stimulation differed somewhat between the two conditions. In saccade conditions, subjects foveated a cross, then had a brief period of smeared foveal input during the saccade itself, followed by

foveation of the target stimulus (“1”). This was compared to control conditions in which they foveated a “0” immediately followed by a “1”.

The second type of control condition better approximates foveal stimulation by matching the first foveal stimulus (usually a cross) and introducing a brief blank period between it and the target stimulus. The blank period is intended to approximate the time the eyes were in motion in saccade conditions. For example, in the experiments of Yarrow et al. (2006a) and Yarrow et al. (2006b) running averages were calculated for saccade duration, and these were used to make sure that the blank period was precisely matched to the duration of the saccade. In fact, this level of precision is probably not required. Yarrow et al. (2004a) ran an experiment evaluating perceived duration in four variants of the standard control condition. The cross changed to the target stimulus either immediately, after 50 ms, after 100 ms, or after 500 ms. Duration estimates were very similar in all conditions, so the presence of a gap doesn’t seem to affect perceived duration (although it does affect temporal order judgements; Yarrow et al., 2006a). Overall, these sorts of control conditions do a reasonable job of matching *foveal* stimulation under the assumption of saccadic suppression, but leave open the issue of whether the visual motion sensed during the saccade might yield a chronostasis effect.

A third type of control condition attempts to answer this concern by having the critical visual objects in the control condition move in a way that approximates their motion on the retina in the saccade condition. In a recent example, Yarrow et al. (2004a) (Experiment 3) had subjects fixate a cross, while a second cross was displayed 20° away on the screen. Both crosses were reduced in contrast, then moved with near saccadic velocity (200° per second) such that the second cross moved towards fixation and the first

cross moved away from fixation in a consistent manner. Half way through this movement, the second cross changed into the target stimulus (a circle). At the end of the movement, subjects were left fixating this circle (now at full contrast) and made a judgement about the duration for which they had fixated it. This condition was compared with two variants of the more typical control condition, and yielded very similar PSEs.

Taken collectively, these results make saccadic chronostasis arising from foveal visual factors rather unlikely. However, it is currently uncertain whether full field visual motion exactly matching that occurring during a saccade could yield a chronostasis effect. For this reason, further experimentation is required. If stimuli were presented via a mirror that could be rapidly rotated, it would be possible to produce full field motion with a saccadic time course (e.g. Diamond, Ross & Morrone, 2000). Duration estimates could be assessed for a stimulus brought to fixation using this approach, and compared with a matched saccadic condition, so that chronostasis could be positively demonstrated over and above full visual field stimulation.

10.3.3 Is it really the first interval that is being affected?

The standard chronostasis procedure involves comparing one interval with one or more subsequent intervals. This procedure cannot distinguish between biases that affect the first interval, and those that affect later intervals in the opposite direction. Our assertion that the first interval is subjectively lengthened is, however, supported by our results using a temporal order judgment procedure (Yarrow et al., 2006a). It is further supported by an experiment in which a different kind of duration judgement was

required. Yarrow et al. (2006b, Experiment 5) presented only a single post-saccadic stimulus (in these experiments a moving circle) and had subjects make absolute duration estimates (in ms) to evaluate its perceived duration. As expected, estimates were higher in the saccade condition compared to the control condition.

10.3.4 Is saccadic chronostasis an artefact of correcting presentation times in order to calculate points of subjective equality relative to the moment of foveation?

In the standard saccadic chronostasis procedure, the PSEs reported in saccade conditions are not simply calculated using the duration for which the target stimulus appeared on the screen in each trial (see Figure 10.1). These PSEs incorporate an additional correction to display times. The rationale for this correction is as follows. The target stimulus changes into its post-saccadic state during the saccade, at a time when perception is degraded (Ross et al., 2001). We have assumed that it is not perceived to a degree compatible with the initiation of a mental timing operation until it is actually foveated. Hence, the time for which the stimulus was on screen during the saccade (the period from stimulus change to saccade termination; D_S in Figure 10.1) is subtracted from presentation times before PSEs are calculated. The effects we report (the difference between control and saccade PSEs) can therefore be broken down into two components: An increase in perceived duration relative to the on-screen presentation time, and our correction.

If this correction is not justified there are two implications. Firstly, the magnitude of the saccadic chronostasis effect would be overestimated. Note, however, that in all

saccadic chronostasis experiments reported to date, omitting the correction would not have eliminated or reversed the direction of the effect. Put another way, we always obtain an increase in perceived duration relative to on-screen presentation time, even before the correction is applied.

A second implication, however, is more critical for the antedating hypothesis. The finding that the magnitude of saccadic chronostasis increases with saccade duration provides an important foundation for this account. In the original experiment reporting this effect (Yarrow et al., 2001, Experiment 1), the change to the target stimulus was triggered based on a set proportion of the distance into the saccade. This means that the size of the correction varied in the short and long saccade conditions, being larger in the latter case. Hence, if the correction is unwarranted, the saccade size difference may be artificially enhanced.

Because of its importance for interpreting the saccade length effect, the appropriateness of the correction was tested by Yarrow et al. (2001, Experiment 1c). They compared two saccadic conditions, both of which employed a very large eye movement. In one condition, the change to the target stimulus was triggered very near the beginning of the saccade. In a second condition, it was triggered very near the end of the saccade. Recall that our correction equals the interval from the change trigger to the end of the saccade. This means that the size of the correction was large in the first condition and small in the second condition. Consider first the hypothesis that subjects did not perceive the mid-saccadic change of stimulus, or were uncertain about its timing, and antedated their subsequent percept to a moment just before saccade initiation regardless of this event. In this case, we would expect corrected PSEs to be identical in both

conditions, but uncorrected PSEs to vary by the same interval that separated the trigger times in the two conditions. Now consider the alternative hypothesis that subjects perceived the mid-saccadic change of stimulus and used it as the start point in estimating the duration of the post-saccadic stimulus, with chronostasis yielding some constant addition to this estimate. In this case, we would expect corrected PSEs to differ by an amount equal to the temporal separation between the two trigger times, but uncorrected PSEs should not differ.

In this experiment, the interval between trigger times was 85 ms. We originally reported *corrected* PSEs, which differed by only 11 ms. This difference in PSEs was not significant, supporting the antedating view. There is an interpretational issue here because the conclusion depends upon a negative result (power = 0.71 two tailed, 0.8 one tailed). A reanalysis of the data from this control experiment using *uncorrected* PSEs shows a significant 75 ms difference ($t = 2.0$, $df = 9$, one-tailed $p = 0.036$), thus providing more positive support for the antedating account.

Hunt et al. (2008) have recently challenged the validity of the correction procedure based on a different kind of experiment. Their subjects made a 25° saccade from a cross to a counter initially showing a “0”. The counter changed to a “1” mid saccade, but only after the very brief (25 ms) presentation of either an “x” or a “+” at the same location. Subjects were asked to discriminate between these two symbols, and indeed were able to do so. Hunt et al. (2008) therefore conclude that in saccadic chronostasis experiments, subjects are able to see the mid-saccadic change to the target stimulus, and that the correction is therefore flawed, undermining the saccade size difference effect. We believe their conclusion is unwarranted because Hunt et al.’s

subjects were performing a very different task to the one typically required in chronostasis experiments. They were asked to discriminate a brief mid-saccadic event rather than judge the duration of a post-saccadic stimulus. This difference implies attending to the stimuli in different ways. Furthermore, the stimuli they used were probably larger and therefore more easily discriminated than those used in our experiments (although it is difficult to be certain because they report the point size of the typeface rather than the visual angle subtended). The impact of the mid-saccadic stimulus change is better assessed in the same context used to demonstrate chronostasis in the first place, as in the trigger time experiment reported above. The question is not whether a mid-saccadic stimulus change can be perceived. The question is whether it is used as a time marker in saccadic chronostasis experiments.

In order to determine conclusively whether the saccade size effect is real or an artefact, we have conducted an experiment comparing saccades of different sizes (Yarrow et al., 2006a). We introduced a critical procedural change in this experiment. Instead of triggering the change to the target stimulus a set proportion of the distance into the saccade, this change was triggered at a similar time relative to the *end* of the saccade. Hence for both long and short saccades, the change was triggered around 30 ms before the target was fixated. The correction applied to PSEs was therefore *virtually identical in both conditions*. We nonetheless obtained a significant difference between PSEs in long and short saccade conditions. This finding provides clear evidence for a saccade size effect in saccadic chronostasis that cannot be ascribed to our correction technique and accords with the antedating account.

10.3.5 Is saccadic chronostasis really a perceptual phenomenon?

Do we really see (or recall seeing) an extended interval following a saccade, or could saccadic chronostasis result from some kind of response bias? In most chronostasis experiments, subjects judge the first interval relative to subsequent intervals, so a simple bias to respond “longer” would yield reduced PSEs. However, saccadic chronostasis is measured relative to a control condition so any bias would have to be specific to saccade conditions. Perhaps, then, the presence of a saccade biases subjects towards making a “longer” response for some non-perceptual reason? This is also unlikely, because the effect has been demonstrated when judgements are made about whether the second interval is longer or shorter than the first (Yarrow et al., 2004a, Experiment 4). In this case, subjects tended to respond “shorter” with equal display durations. Our method, however, cannot be said to be “criterion free” in the sense derived from signal detection theory. For example, it is possible that our subjects employed some sort of high level reasoning strategy in reaching their decisions. Although we asked our subjects to judge how long they *saw* the post-saccadic stimulus for, they might have reasoned that this stimulus appeared during their saccade. Hence the display may have given rise to demand characteristics that encouraged subjects to compensate for their own saccades. We cannot completely discount this possibility, but the differences we find for saccade extent imply that this strategy would have to be extremely sophisticated. Moreover, this account does not fit with the phenomenology of the task. In our experience as observers there is no sense of adding time or interpreting ones eye movements, only of accurately reporting a percept.

10.4 Saccadic chronostasis and other temporal illusions

Since the term “chronostasis” was first coined to describe the saccadic illusion that forms the focus of this paper, a number of other illusions have been described and explicitly related to the effect. Alexander, Thilo, Cowey & Walsh (2005; see also Hodinott-Hill et al., 2002) played subjects five tones bounding four consecutive intervals. The tones were either presented all to one ear (the control condition) or the first tone to one ear and all subsequent tones to the other ear. The first interval seemed prolonged in comparison to the subsequent intervals when the auditory stimuli bounding it were presented to different ears, with PSEs reduced by around 160 ms compared to the control condition. In a subsequent experiment, the tones were presented to the same ear in all conditions, but features of the two tones bounding the first interval were manipulated. Increasing the volume of the second tone yielded somewhat reduced PSEs (an effect of around 50 ms) but no effect was obtained when the volume of the first tone was increased, or when the pitch of the second tone was changed.

Hodinott-Hill et al. (2002) and Alexander et al. (2005) argue that these effects are linked to saccadic chronostasis. They also consider the manual chronostasis effects described next, as well as the sequential effect reported by Rose & Summers (1995), in which the first and last stimuli in a sequence of four are overestimated, to be members of the same family. They make this argument based on parsimony, and a broad similarity in the direction and magnitude of these effects. They then go on to offer an explanation based on arousal and/or action increasing the rate of a hypothetical internal clock. We

feel that the grouping together of these particular illusions and the exclusion of other temporal biases is rather arbitrary. At face value, the procedures used by Alexander et al. (2005) have more in common with those employed by Grondin and co-workers, who have shown temporal biases when visual bounding stimuli appear at different spatial locations (Grondin, 1998) and when auditory bounding stimuli have different spectral properties (Grondin & Rousseau, 1991), than they do with typical demonstrations of saccadic chronostasis. Furthermore, when we formulated predictions based on the arousal account and tested them experimentally, we found no evidence that it could explain the saccadic chronostasis illusion (Yarrow et al., 2004a; see section 10.2.2 above). The effects we have obtained using temporal order judgements also seem inconsistent with it.

Other temporal illusions motivated by the saccadic chronostasis finding have also been described. Yarrow & Rothwell (2003) asked subjects to make reaching movements towards a vibrating tactile stimulus which marked out target and reference intervals. Subjects overestimated the duration of the post-movement interval by 60-120 ms compared to a static control condition, but the size of the effect did not change for reaches of different extents/durations. Yarrow & Rothwell (2003) also tested conditions in which subjects viewed a sequence of visual intervals initiated by reaching to and/or pressing a button. PSEs for the first interval did not differ between movement and control conditions in any of three experiments, with experimental powers ranging from 0.8 to 0.99. The contrast between reaching to a tactile stimulus and having a reach/button press trigger a visual stimulus led Yarrow & Rothwell (2003) to speculate that the tactile effect depended upon uncertainty regarding the physical onset of the target stimulus. Subjects could feel the vibrator as soon as they touched it, but could not know exactly when it had

been switched on. In visual conditions, there was no uncertainty because the visual stimulus was constantly fixated. However, in a different experiment that maintained an even closer correspondence to the saccadic chronostasis procedure, the first interval in a visual sequence was not subjectively prolonged in a patient with congenital ophthalmoplegia, who made “saccadic head movements” to a digital counter (Jackson, Newport, Osborne, Wakely, Smith & Walsh, 2005). In this case, uncertainty would seem to be present, but no effect was reported.

In contrast to Yarrow & Rothwell's (2003) results, other groups have obtained chronostasis-like effects when a button press initiates a sequence of visually defined intervals. Park et al. (2003) initiated a digit sequence either randomly, 500 ms after a key press, or immediately after a key press. PSEs for the first interval were reduced by around 70 ms when the key press initiated the sequence compared to the random and delayed conditions. Park et al. (2003) also observed a similar effect when a vocal signal initiated the digit sequence. In a different set of experiments, Hunt et al. (2008) found a key press effect of around 70 ms in two experiments using a digit sequence, but not in three rather similar subsequent experiments. The exact conditions that give rise to this effect have yet to be pinned down.

If many different kinds of movement give rise to chronostasis-like effects, what common mechanism might explain these results? Park et al. (2003) suggest that another temporal illusion occurring in the context of movements might be responsible for their findings. Haggard, Clark & Kalogeras (2002) have reported that when a brief auditory stimulus is presented shortly after a button press, and is contingent upon that action, the subjective estimate of the action's time of occurrence is shifted in the direction of the

auditory stimulus. Furthermore, the subjective time of occurrence for the auditory stimulus is shifted in the direction of the action, prompting these authors to label this effect “intentional binding”. Generalising this result, it is possible that *any* action shifts the perceived time of its sensory consequences towards the action. When such sensory consequences mark the first boundary of an interval, we might therefore expect the perceived duration of that interval to be increased.

Are intentional binding and chronostasis related? One approach to answering this question would be to explore in detail the psychophysical properties of each illusion and see how they compare. For example, intentional binding arises only when actions are made voluntarily (Haggard et al., 2002). The effect is actually reversed when a movement is initiated in the absence of volition (by using trans-cranial magnetic stimulation over primary motor cortex). Saccadic chronostasis, however, occurs with a similar magnitude for voluntary and highly automatic classes of saccades. This dissociation implies that the two illusions may result from different kinds of mechanisms (Yarrow et al., 2004b). One could also ask whether other illusions share properties we have demonstrated for saccadic chronostasis, such as a constant effect size regardless of stimulus duration (Yarrow et al., 2004a) and a shift in the perceived time of the event that initiates the critical interval (Yarrow et al., 2006a). We already know, for example, that while saccadic chronostasis depends upon the duration of the preceding movement, tactile chronostasis does not (Yarrow & Rothwell, 2003). Another possibility would be to assess the strength of each illusion using the same subject group and look for correlations. It is possible that there is a common mechanism underlying some or all of the biases described here, or that such a mechanism may be supplemented by more specific mechanisms in particular cases.

However, at this point such links seem quite speculative. We prefer to view these psychophysical biases as separate until some convincing evidence emerges to link them. In our view, much of the confusion regarding common mechanisms in chronostasis arises from confusing action-specific effects with sequence position effects. We are not aware of any evidence implying that these kinds of effects are related.

10.5 Conclusions

When observers saccade towards a visual target, they overestimate the duration for which it is presented. We have conducted extensive investigations of this illusory bias, and favour an antedating account in which the saccade target is subjectively experienced as having been fixated since before the eye movement began. This account explains why we have no temporal experience corresponding to the period of our saccades, and therefore helps explain our conscious experience during active vision. Although a number of other illusory biases have been linked with saccadic chronostasis, their relationship to it remains currently unclear. Where direct evidence linking these effects has been sought, it has generally not been obtained. Hopefully, further research will allow the mechanisms underlying these various biases to be better understood.

References

- Alexander, I., Thilo, K. V., Cowey, A., & Walsh, V. (2005). Chronostasis without voluntary action. *Experimental Brain Research*, *161*, 125-132.
- Allan, L. G. (1979). The perception of time. *Perception and Psychophysics*, *26*, 340-354.

- Brown, P. & Rothwell, J. C. E. (1997). Illusions of time. *Society for Neuroscience Abstracts, 27th Annual Meeting, 23*, 1119.
- Campbell, F. W. & Wurtz, R. H. (1978). Saccadic omission: why we do not see a grey-out during a saccadic eye movement. *Vision Research, 18*, 1297-1303.
- Diamond, M. R., Ross, J., & Morrone, M. C. (2000). Extraretinal control of saccadic suppression. *Journal of Neuroscience, 20*, 3449-3455.
- Duhamel, J. R., Colby, C. L., & Goldberg, M. E. (1992). The updating of the representation of visual space in parietal cortex by intended eye movements. *Science, 255*, 90-92.
- Fischer, B. & Ramsperger, E. (1984). Human express saccades: extremely short reaction times of goal directed eye movements. *Experimental Brain Research, 57*, 191-195.
- Grondin, S. (1998). Judgments of the duration of visually marked empty time intervals: linking perceived duration and sensitivity. *Perception and Psychophysics, 60*, 319-330.
- Grondin, S. & Rousseau, R. (1991). Judging the relative duration of multimodal short empty time intervals. *Perception and Psychophysics, 49*, 245-256.
- Haggard, P., Clark, S., & Kalogeras, J. (2002). Voluntary action and conscious awareness. *Nature Neuroscience, 5*, 382-385.
- Hellstroem, A. (1985). The time-order error and its relatives: Mirrors of cognitive processes in comparing. *Psychological Bulletin, 97*, 35-61.

- Hodinott-Hill, I., Thilo, K. V., Cowey, A., & Walsh, V. (2002). Auditory chronostasis: Hanging on the telephone. *Current Biology*, *12*, 1779-1781.
- Hopp, J. J. & Fuchs, A. F. (2002). Investigating the site of human saccadic adaptation with express and targeting saccades. *Experimental Brain Research*, *144*, 538-548.
- Hunt, A. R., Chapman, C. S., & Kingstone, A. (2008). Taking a long look at action and time perception. *Journal of Experimental Psychology: Human Perception and Performance*, *34*, 125-136.
- Jackson, S. R., Newport, R., Osborne, F., Wakely, R., Smith, D., & Walsh, V. (2005). Saccade-contingent spatial and temporal errors are absent for saccadic head movements. *Cortex*, *41*, 205-212.
- Nakamura, K. & Colby, C. L. (2002). Updating of the visual representation in monkey striate and extrastriate cortex during saccades. *Proceedings of the National Academy of Sciences of the United States of America*, *99*, 4026-4031.
- Park, J., Schlag-Rey, M., & Schlag, J. (2003). Voluntary actions expands perceived duration of its sensory consequence. *Experimental Brain Research*, *149*, 527-529.
- Rose, D. & Summers, J. (1995). Duration illusions in a train of visual stimuli. *Perception*, *24*, 1177-1187.
- Ross, J., Morrone, M. C., Goldberg, M. E., & Burr, D. C. (2001). Changes in visual perception at the time of saccades. *Trends in Neurosciences*, *24*, 113-121.

Sasaki, T., Suetomi, D., Nakajima, Y., & ten Hoopen, G. (2002). Time-shrinking, its propagation, and Gestalt principles. *Perception and Psychophysics*, *64*, 919-931.

Sommer, M. A. & Wurtz, R. H. (2002). A pathway in primate brain for internal monitoring of movements. *Science*, *296*, 1480-1482.

Treisman, M., Faulkner, A., Naish, P. L., & Brogan, D. (1990). The internal clock: Evidence for a temporal oscillator underlying time perception with some estimates of its characteristic frequency. *Perception*, *19*, 705-743.

Umeno, M. M. & Goldberg, M. E. (1997). Spatial processing in the monkey frontal eye field. I. Predictive visual responses. *Journal of Neurophysiology*, *78*, 1373-1383.

Walker, M. F., Fitzgibbon, E. J., & Goldberg, M. E. (1995). Neurons in the monkey superior colliculus predict the visual result of impending saccadic eye movements. *Journal of Neurophysiology*, *73*, 1988-2003.

Wearden, J. H., Edwards, H., Fakhri, M., & Percival, A. (1998). Why "sounds are judged longer than lights": Application of a model of the internal clock in humans. *Quarterly Journal of Experimental Psychology B: Comparative and Physiological Psychology*, *51*, 97-120.

Yang, Z. & Purves, D. (2003). A statistical explanation of visual space. *Nature Neuroscience*, *6*, 632-640.

Yarrow, K., Haggard, P., & Rothwell, J. C. (2004a). Action, arousal, and subjective time. *Consciousness and Cognition*, *13*, 373-390.

Yarrow, K., Whiteley, L., Haggard, P., & Rothwell, J. C. (2006a). Biases in the perceived timing of perisaccadic visual and motor events. *Perception and Psychophysics*, *68*, 1217-1226.

Yarrow, K., Whiteley, L., Rothwell, J. C., & Haggard, P. (2006b). Spatial consequences of bridging the saccadic gap. *Vision Research*, *46*, 545-555.

Yarrow, K., Haggard, P., Heal, R., Brown, P., & Rothwell, J. C. E. (2001). Illusory perceptions of space and time preserve cross-saccadic perceptual continuity. *Nature*, *414*, 302-305.

Yarrow, K., Johnson, H., Haggard, P., & Rothwell, J. C. E. (2004b). Consistent chronostasis effects across saccade categories imply a subcortical efferent trigger. *Journal of Cognitive Neuroscience*, *16*, 839-847.

Yarrow, K. & Rothwell, J. C. E. (2003). Manual chronostasis: Tactile perception precedes physical contact. *Current Biology*, *13*, 1134-1139.

Figure legends

Figure 1. Schematic of the saccade condition from a typical experimental task. D_S represents the duration for which the post-saccadic target stimulus is displayed on screen during the saccade. D_F represents the duration for which it is subsequently fixated. D_R represents the duration for which a reference stimulus is presented. The display time of the post-saccadic stimulus ($D_S + D_F$) is varied from trial to trial. A consistent finding is that subjects feel as though they have seen the post-saccadic stimulus and the reference stimulus for identical durations when D_F is significantly lower than D_R .

Figure 1

