Temporal illusions subsequent to movement

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Abstract

When 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 position. For a short period, the second hand appears to have stopped; then, suddenly, it ticks on. This phenomenon is of intuitive interest as an experience that many people recognise, and formed the starting point of the research described here. A comparison methodology was employed in which subjects judged the perceived duration of a visual stimulus relative to that of subsequent stimuli. The duration of the first stimulus varied across trials, permitting the derivation of a matched time at which subjects felt the stimuli to be of equal duration. When the first stimulus was fixated immediately after a saccade, lower matched times were obtained relative to constant fixation conditions, indicating that subjective time had been stretched out. This effect is termed saccadic chronostasis. The methodology permitted accurate quantification of saccadic chronostasis under various task conditions. Manipulations explored include movement size, movement type (saccades of various types, hand/arm movements), the nature of the stimulus that is to be judged and its relationship to other perceptual objects. Key results include the illusion's dependency upon both saccade size and the continuity of certain components of the visual scene. Similarities and important differences emerged when the paradigm was extended to arm movements (manual chronostasis). Chronostasis offers a novel insight into the integration of action and perception, with implications for theories of perceptual continuity across movements. It is an illusion of time, and must be dealt with by theories that seek to explain temporal perception, but also has more general relevance when considering the manner in which conscious experience emerges from a sequence of sensory events. These issues inform an initial characterisation of the effect.
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Publications, collaborations and acknowledgements

Experiments 1a, 1b, 1c, 1d, 2a and 2b have previously been published in the following article:


Experiment 6a was conducted in collaboration with Lisa Webster, and has also been included in her final project contributing towards the degree of MSc (Clinical Neuroscience; UCL).

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Chapter 1: Introduction

The accurate representation of time is a fundamental requirement for humans. It underlies both perception within a dynamic environment and the production of co-ordinated behaviour. Timing is ubiquitous, woven into the fabric of sensory and motor processes, whether it is explicitly represented/controlled or arises indirectly as an emergent property of a given system. Despite its central role, time perception is not as well understood as sensory modalities like vision and touch, perhaps because we lack an obvious dedicated organ for its measurement. The research to be described in the bulk of this thesis relates to a particular illusion of timing that occurs in the context of movement and may therefore shed light upon perception in dynamic contexts. This illusion has not been described previously, so no substantial body of work is available to summarise at this point. The handful of experiments that appear of most direct relevance are dealt with in greater detail in the experimental chapters that follow. Here, a selective review of previous timing-related research is presented to provide some general orientation for the reader.

The retrospective/prospective distinction in interval timing.

Estimating the length of a given interval of time may occur in two fundamentally different contexts; the retrospective and prospective paradigms. Experiments investigating retrospective duration judgements typically involve misleading subjects by engaging them in some task before surprising them by asking them to estimate the length of time for which they have been occupied with it. Hence each subject can provide only a single data point. In prospective duration judgements, the subject knows in advance that their task is to judge the passage of time in some manner. This approach is generally preferred because it permits numerous trials to be conducted with a single subject. There is considerable evidence that retrospective and prospective duration judgements are carried out by separate mechanisms (Block and Zakay, 1997). The function relating
perceived time to stimulus time differs for these tasks, with long durations being underestimated under conditions of retrospective timing. Additionally, timing in the two conditions is differentially affected by variables like processing difficulty and stimulus complexity. In general, retrospective timing is best explained by models that view timing as indirect, an inference based on the perception and processing of events (Block, 1990). Examples include memory storage models (Ornstein, 1969) where perceived time relates to the storage size of memories encoded in a given interval, and memory change models (e.g. Block and Reed, 1978) where changes in environmental context, shifts in processing requirements and so forth relate to perceived duration. These models tend to be rather vague. They have little obvious relevance to the tasks used in forthcoming experimental chapters, so will not be further discussed here.

Characteristics of prospective interval timing. Prospective timing has been studied using a considerable variety of tasks. Following Allan’s (1979) broad ranging review, four broad classes can be considered. In verbal estimation, the subject perceives a stimulus of a given interval and reports its length in absolute terms. In production, the experimenter states an interval verbally and the subject produces that interval, by pressing a key for example. In reproduction, the subject is presented with a stimulus of a given interval, then produces it. In comparison, the subject perceives two or more intervals (often, but not necessarily, in rapid succession) and makes some forced-choice relative judgement about their lengths. Note that both production and reproduction overlap with studies of motor timing, reviewed in a later section.

In general, prospectively assessed subjective duration has two established properties. Firstly, the function relating perceived time to stimulus time (the psychophysical law for time perception) is monotonic, most likely a power function with an exponent very close to 1 or a simple linear function (Allan, 1979). Hence the timing system is both flexible (in the sense of being applicable over a large range of durations) and accurate,
with mean perceived time equalling objective time (Malapani and Fairhurst, 2002). With very fine grain analysis, reproduced time may however exhibit a systematic oscillation relative to a purely linear function, perhaps indicative of underlying discreteness in timing (Collyer, Broadbent, and Church, 1992).

A second key finding is that a positive relationship exists between variability in time judgements and the time being judged (Weber’s law applied to timing). Specifically, the relationship appears to be linear between the standard deviation of subjective time and mean subjective time, although once again more fine-grained analysis may yield step-like deviations from strict linearity (Kristofferson, 1980). This finding is often referred to as the scalar property (e.g. Gibbon and Church, 1990).

Aside from these general findings, there are a large number of non-temporal factors that influence time judgements (the following summary being by no means exhaustive). The order of stimulus presentation can have a very marked effect on judgements, most notably in comparison methodologies, a bias known as the time order error (Allan, 1979; Hellstroem, 1985). A related phenomenon that nonetheless appears to have some distinctive qualities is the tendency of an initial stimulus (S1) to shorten the perception of a subsequent stimulus (S2) when S1’s duration falls in a critical range just below that of S2 (Allan and Gibbon, 1994; Sasaki, Suetomi, Nakajima, and ten Hoopen, 2002). Such “time shrinking” has been demonstrated only for unfilled auditory stimuli demarcated by clicks, but other contextual illusions have been found for vision. Rose and Summers (1995) for example have reported that the first square light stimulus in a sequence of four is overestimated in duration, as is the final such stimulus. High frequency trains of “arousing” clicks can result in both a general overestimation of the duration of subsequent stimuli and a specific frequency-dependent modulation (Treisman, Faulkner, Naish, and Brogan, 1990). Stimulus properties themselves are also important for perceived duration. Auditory stimuli are generally judged to be longer than visual stimuli of identical duration (Wearden, Edwards, Fakhri, and Percival,
Filled intervals tend to be judged longer than unfilled intervals (empty periods marked by events at either end) and the intensity and nature of a filled interval (or the events marking an unfilled interval) can influence perceived duration. Higher level factors have also been found to influence the perception of time. Multitasking manipulations intended to reduce the availability of attentional resources tend to lead to an underestimation of the passage of time (e.g. Burle and Casini, 2001; Macar, 2002). Finally, the amount of time between the perception and report of a stimulus can have an effect, with temporal representations appearing to shrink over time (Wearden, Parry and Stamp, 2002).

**Models of interval timing behaviour.**
A number of information-processing models have been proposed to deal with the effect of specific manipulations on prospective time perception, but not all have attempted to address the whole range of timing phenomena in a single framework (Allan, 1979). For those that have, the dominant template has been the pacemaker-accumulator internal clock (Treisman, 1963). A timer sends out pulses that, when a switch is closed, amass in a temporary store and can subsequently be compared with values stored in long-term memory. The basic architecture of the model deals well with the psychophysical law, and specific instantiations can handle scalar variability.
One such instantiation is the temporal information-processing model developed in scalar expectancy theory (SET; Gibbon, 1981). The SET model posits a number of specialised components, with temporal information passing between them. A schematic is presented in Figure 1.1. It has gained considerable support from both animal and human timing studies (Allan, 1998) although controversy remains regarding the specific mathematical formalisations that best describe its functioning at each level (e.g. Rodriguez-Girones and Kacelnik, 2001).

Recently, attempts have been made to map the influence of the previously discussed non-temporal factors onto the components of such a model (e.g. Franssen and Vandierendonck, 2002). A major focus has been the role of the pacemaker, which is assumed to vary its rate based on arousal levels. This proposal allows the model to cope with effects like those of high frequency trains of clicks, increases in body temperature and stimulus intensity, and changes in modality (i.e. auditory compared to visual), all of which increase time estimates (or decrease reproduction times) in a manner consistent with increased pacemaker speed (Penton-Voak, Edwards, Percival, and Wearden, 1996; Treisman, 1963; Wearden et al, 1998; Wearden and Penton-Voak, 1995). Regarding higher level attentional factors, two broad approaches are taken to incorporating these effects. In the “flickering switch” approach, multitasking leads to division of attention, with the switch only closing when attention is directed to the timing task. This approach implies a fundamentally serial process, and can be identified with bottleneck theories of attention (e.g. Pashler, 1994). The second approach posits the existence of an additional component, an “attentional gate” lying between the switch and the accumulator that permits only a proportion of emitted pulses through, depending upon allocation of attention to the timing task. Hence the theory draws on graded resource sharing approaches to dual-task performance (e.g. Wickens, 1984). The value of this additional component (i.e. its additional explanatory power relative to the incumbent increase in model complexity) is a matter of ongoing debate (Lejeune, 1998; Lejeune, 2000; Zakay, 2000).
There has also been interest in mapping the various clock components onto brain structures, despite continuing objections that the model lacks neural plausibility. Patient studies implicate the basal ganglia and lateral cerebellum as key regions for timing (Meek and Benson, 2002; Hazeltine, Helmuth and Ivry, 1997). In general, both parkinsonian and cerebellar patients are impaired at both sensory and motor timing tasks. Pharmacological interventions in animals again suggest the basal ganglia (Meck, 1996) with dopaminergic agonists seeming to selectively increase the speed of the pacemaker. Administration during the test phase of an experiment in which an animal has been conditioned to respond at a given time causes the animal to immediately begin responding earlier, with a gradual return to correct responding as reference memory values are slowly re-established. Removing the drug then causes late responding, until reference values are once again recalibrated at the new pacemaker rate. For dopaminergic antagonists, the whole pattern is reversed. Pharmacological studies are less clear cut in humans, but imaging experiments offer mixed support for the involvement of these areas along with the supplementary motor area, dorsolateral prefrontal cortex, anterior cingulate cortex and right parietal cortex (Macar, Lejeune Bonnet, Ferrara, Pouthas, Vidal, and Maquet, 2002; Rao, Mayer, and Harrington, 2001). The manner in which the clock model's components are implemented in these neural regions is, however, hotly debated (Lewis, 2002). Related models have been proposed that eschew the pacemaker-accumulator architecture and its cognitive “black box” approach in favour of a clear physiological basis. One example, the striatal beat frequency model proposed by Matell and Meck (2000) shares many of the psychological properties of SET but suggests a timing mechanism based on the striatum's ability to detect coincident patterns of cortical oscillations. As yet, this model and various other contenders to the throne of biological plausibility have not generated as much research as SET and it is still unclear what kind of model will eventually provide the best description of timing behaviour.
Motor timing. While all action evolves over time, it is reasonable to contrast motor acts that are explicitly timing based with those that are simply well co-ordinated. Although there is clear crossover between some of the previously discussed methods used to assess interval timing (i.e. production, reproduction) and motor timing, the latter has typically been assessed in the context of repetitive (rhythmic) action generation rather than the estimation of discrete intervals. Broadly, two approaches dominate this literature (Schoener, 2002). To characterise crudely, dynamical approaches focus on coupled oscillatory mechanisms and tend to view timing as an emergent physiological/mechanical property (Kugler and Turvey, 1987). By contrast, information-processing approaches posit timekeepers rather like that discussed in the previous section. For the sake of continuity, brevity, and relevance to the discrete timing task employed in the experimental chapters that follow, the focus here is on the information-processing approach.

The tapping paradigm. The most commonly employed task in motor timing is synchronised tapping, with or without continuation. Subjects tap along with a metronome at a given frequency (synchronisation). They may also be required to continue to tap at the same rate when the metronome has stopped (continuation). Both phases clearly require an internal representation of time; subjects do not simply react in the synchronisation phase, in fact showing a tendency to slightly anticipate the metronome (discussed in the following section). Continuation, however, offers an opportunity to study motor timing in the absence of sensory feedback that might provide corrective cues. The paradigm was introduced by Stevens (1886) but was revived in the 1970s to provide the basis of the Wing-Kristofferson model (Wing and Kristofferson, 1973, reviewed in Wing, 2002). The model was inspired by the observation that the length of a reproduced interval tends to have a negative correlation with those intervals produced immediately before and after it. It provided a formal mathematical description based upon a hierarchical two-level process (an internal
timekeeper and a motor implementation delay) with the two processes operating as independent sources of variability. Hence the timekeeper provides a central signal for the initiation of each tap, with finger movement processes producing a (variable) delay before the tap actually occurs. In general, the autocorrelation pattern predicted by the model is well conformed to, although alternative analyses of tapping data have produced some inconsistent results (e.g. Ding, Chen and Kelso, 2002). The Wing-Kristofferson model permits clock variability and motor variability to be dissociated and quantified and has been widely employed for this purpose. As predicted from the previous discussion of scalar timing, clock variability increases linearly with the interval that is being reproduced while motor variability remains constant.

Motor timing studies lead quite naturally to a consideration of more complex rhythmic production, permitting speculation regarding the uniqueness of any clock component (i.e. does the production of a complex rhythm depend upon a single clock or a hierarchy of clocks with similar operating principles). One finding that suggests the existence of more than one clock (aside from the general ubiquity of timed operations in human behaviour) is that variability decreases when taps are made with two hands rather than just one (Helmut and Ivry, 1996). This variability decrease arises in the clock itself, not processes of motor implementation, as indexed by decomposition based on the Wing-Kristofferson model. Ivry and Richardson (2002) have therefore suggested a multiple timer model in which effectors are controlled by separate clocks. When bimanual tapping is performed, the output of the two clocks is centrally gated and summed for comparison with a combined threshold before simultaneous movement commands are sent to both hands. This process yields a prediction of decreased variability relative to reliance on a single clock, conforming well with data. It should be noted, however, that an alternative account based on increased sensory reafferent information is also plausible (Drewing, Hennings and Aschersleben, 2002).
**Interaction of timing systems.** Introducing the idea of separate clocks highlights the related issue of the independence of motor and perceptual timing. The distinction between motor and purely perceptual indices of interval timing was blurred by the rather general treatment provided in the earlier sections on duration judgements. In general, different methods can give rise to quite different results (Allan, 1979) but where perceptual and motor timing have been explicitly compared there is good evidence for a common mechanism. The previously mentioned patient studies, for example, have often found similar impairments for both types of task. Manipulations considered to affect pacemaker rate tend to influence both perceptual and motor tasks in the predicted manner (e.g. Treisman et al, 1990; Treisman, Faulkner and Naish, 1992). Correlations have also been found to be high for performance measures on sensory and motor timing tasks (e.g. Keele, Pokorny, Corcos and Ivry, 1985, although in this study the correlation was unpredictably reduced when only the clock variance component of the motor task was used). Interestingly, these correlations extend to motor tasks with explicit timing goals but not those where timing emerges naturally from cyclical movement production. Hence sensory timing correlates with both tapping and circle drawing with pauses inserted between each circle, but not continuous circle drawing performed at a pre-specified rate (Zelaznik, Spencer and Ivry, 2002). For explicitly timed actions, however, common timing mechanisms are implicated in perceptual and motor timing. The research areas show considerable overlap, and motor timing researchers have posited just as wide a variety of alternative models as their sensory counterparts when considering the clock component of timing variability, again with varying degrees of neural plausibility (e.g. Rosenbaum, 2002).

**Point estimation, successiveness and subjective simultaneity.** A quite separate research tradition from that investigating interval timing has instead looked at the perception of simultaneity and successiveness. Coherent perception often involves the integration of information over time
and numerous studies have investigated various types of (typically visual) persistence, be it at a purely sensory or a more abstract “informational” level (e.g. Loftus and Irwin, 1998). The once popular perceptual moment model, which posited a centrally defined, fixed interval of around 100 ms over which integration occurred, has not been well supported (Patterson, 1990). However, there is some evidence that there may be a very brief discrete interval (∼25 ms) operating as a quantal building block for most cognitive operations and perhaps relating to the pulse rate of an internal clock (e.g. Burle and Bonnet, 1999; Collyer, Broadbent, and Church, 1992). Reaction time distributions, for example, appear to cluster at multiples of such an interval (Poppel, 1997).

**Temporal order judgements.** While the general issues of sensory persistence and information integration have been studied with a variety of methods, the temporal order judgement paradigm has been crucial for the investigation of subjective simultaneity and successiveness. Here, two short duration stimuli are presented in close temporal proximity and the subject is required to make a judgement about their order. The method indexes the perception of successiveness, and requires that the two stimuli be different from one another, or presented at different spatial locations, in order to permit a judgement to be made. Hence while this method clearly relates to the situation in which subjects are required to judge whether identical stimuli yield a single as opposed to two distinct percepts, temporal order judgements imply the discrimination of order rather than the sensory integration/differentiation of events. In this sense they reflect mechanisms of relative timing, rather than being a measure of low-level sensory acuity. It is perhaps not surprising, then, that thresholds for successful temporal order judgements are largely consistent across sensory modalities (requiring around 30 ms offset between stimuli for 75% correct performance) whereas successive verses simultaneous judgements for repeated identical stimuli
give rise to very different thresholds for different senses (Hirsh and Sherrick, 1961).¹

As well as asking how close together in time two identical but spatially separate stimuli have to be to permit discrimination of their order, it is possible to use the temporal order paradigm to estimate any bias for perceiving one stimulus to have occurred before the other. This is most obviously relevant when the stimuli differ in some manner. A number of factors, such as stimulus intensity and attentional allocation, can affect order judgements within a modality (Jaskowski, 1999; Shore, Spence and Klein, 2001). A particularly striking finding is that judgements about events from different modalities often exhibit strong biases that are variable between subjects but fairly constant for a given observer (Spence, Shore and Klein, 2001; Stone, Hunkin, Porrill, Wood, Keeler, Beanland, Port, and Porter, 2002). This finding leads naturally to a consideration of how signals processed via different sensory organs with correspondingly different neural pathways are ordered internally, and how this internal ordering manifests itself in consciousness.

**The representation of order.** Conscious awareness of order is not a pure reflection of processing time, because tasks which can be considered to reflect speed of sensory processing (i.e. simple reaction time) dissociate from temporal order judgement tasks. A stimulus which gives rise to a more rapid reaction time is not necessarily perceived to have occurred first when paired with one that yields a slower reaction time (Jaskowski, 1999; Jaskowski and Verleger, 2000). Nonetheless, there are results from alternative paradigms that would seem to suggest that awareness of an event can directly reflect underlying differences in the location and timecourse of neural processing, even within a single sensory modality. When a coloured stimulus moves back and forth in rapid alternation and changes colour at the same frequency as it changes direction, subjects perceive the two changes (in direction and colour) to be simultaneous when the colour change actually

¹ As low as 2 ms for auditory stimuli, with far longer integration times for vision.
precedes the motion change by around 80 ms (Moutoussis and Zeki, 1997a). This effect can also be obtained indirectly by measuring colour-contingent motion after-effects to rotating stimuli, where the phase relationship between a given colour and a given direction of motion is varied systematically for the adapting stimulus (Arnold, Clifford and Wenderoth, 2001). There is also evidence that motor control in synchronisation tasks reflects processing times in a fairly direct manner. When subjects tap in synchrony with a metronome, their taps tend to anticipate the metronome’s beats (see Aschersleben, 2002, for an overview). This error is explicable if subjects are actually attempting to align the auditory sensation with the tactile feedback from each finger tap, given that tactile transmission times are probably greater (although this conclusion rather depends upon which component of the brain response is considered relevant). Although other interpretations have been offered, this simple hypothesis predicts much of the relevant data, including the synchronisation error’s dependency on tapping effector and other manipulations of sensory feedback (Aschersleben and Prinz, 1995).

The interpretation of ordering phenomena in terms of neural delays, sometimes known as the Paillard-Fraisse hypothesis, is therefore well established. To give one classic and rarely disputed example, the Pulfrich effect arises when a pendulum moving from left to right and vice versa is observed with one eye covered by a light-attenuating filter. Under these circumstances, the pendulum appears to follow an elliptical path with an illusory component of motion in depth. The effect can be explained by the difference in transmission latency for dim compared to bright stimuli, given that binocular depth arises in part from relative differences in the position of an object’s image on the retina of each eye. The covered eye’s image is

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2 The effect has, however, been interpreted in different ways. It is dependent upon experimental conditions such as alternation rate, and might be better explained by an interpretative mechanism for event ordering that prefers stimulus changes of a particular type. Hence lining up a change (for colour) with a change in direction of change (for motion; motion = change in position) leads to a bias (Nishida and Johnston, 2002). This explanation cannot, however, account for similar latency differences between form and colour (Moutoussis and Zeki, 1997b) or explain the effect’s dependency on the angle of motion-direction change (Arnold and Clifford, 2002).
transmitted more slowly, yielding a difference in position (given the pendulum's motion). This shift appears to be transformed into depth information by space-time tuned neurones in striate cortex (Anzai, Ohzawa, and Freeman, 2001).

**Objections to the Paillard-Fraisse hypothesis.** There are, however, a number of reasons for doubting the processing delay hypothesis' broader validity. Dennett and Kinsbourne (1992) provide a thorough discussion of the logical pitfalls of considering the conscious experience of the ordering of events to be a simple reflection of the physical ordering of events. They argue that this reasoning reflects incorrect assumptions that effectively posit a single re-presentation of incoming information to an internal observer (the Cartesian theatre model). They raise the important point that information need not be neurally represented according to what it physically represents (and indeed cannot be in the case of features like colour); hence temporal order need not be maintained in any simple isomorphic fashion. They suggest a multiple drafts model in which consciousness emerges over time based on the current state of the entire distributed system, with room for considerable reinterpretation (realignment) when arriving at any conclusion about the ordering of events. In this sense, they emphasise that the interpretation an observer gives will depend upon the sum of currently available information, rather than being an immediate on-line reflection of the arrival order of sensory messages. To bolster their claims, they discuss experimental situations in which sensory stimuli appear to influence conscious perception before their presentation, logically impossible if we accept both on-line consciousness and the laws of cause and effect. To take one example, somatosensory saltation arises when two successive taps to the same skin location are followed by a third tap to a different position with an appropriate delay. Instead of a veridical perception, observers report that the second tap was delivered at a spatial position between the two stimulation sites (Geldard and Sherrick, 1986). Hence, the delivery of the third tap produces a misperception of position for the second tap that appears to have
been experienced before the third tap is delivered. It is difficult to explain this result without applying a framework similar to the multiple drafts model. Note that this theory is not identical to simply stating that there is a fixed delay from stimulation to consciousness in order to take account of the longest processing delay that might reasonable arise. This position is tenable, if we accept that many behavioural responses can arise before (or without) conscious awareness, but still implies an ultimately singular consciousness. Dennett and Kinsbourne (1992) instead suggest that consciousness may arise quite rapidly, but is subjected to a continuous revision process that rarely gives rise to subjective discontinuity despite having settled on a variety of mutually incompatible interpretations at different times.

To this broad ranging account it is also possible to add a number of related objections to the processing delay hypothesis. Firstly, at what neural point is a decision about the order of arrival of signals made (especially given the time-smeared nature of neural representation)? Taking the illustration of an interview conducted over a satellite link to represent discussion between two neural areas (representing, say, visual motion and colour) it is immediately apparent that both parties will feel that the other is delayed relative to themselves (Nishida and Johnston, 2002). Arguing in favour of the immediate emergence of conscious awareness from each region as it processes information cannot sidestep the issue that some other region or regions must make the actual decision about order. A related point relates to the general ability of the brain to predict, or take account of the properties of the physiological system it uses/controls (Mueller, Aschersleben, Koch, Freund, and Prinz, 1999). This capacity for inverse computation appears vital for the control of action (Wolpert and Ghahramani, 2000). Why are we suddenly unable to take account when considering neural delays in the ordering of events?

*An empirical battleground: the flash-lag illusion.* Recently, these arguments have resurfaced in the context of the flash-lag illusion, a bias that
emerges when subjects must identify the position of a moving stimulus at a specific moment in time. In a typical experiment, the empty interior of a continuously moving black ring is filled with a flash at a given moment. Observers have the clear experience that the moving ring was slightly ahead of the stationary flash (which consequently fails to fill the entire ring). In the decade since the illusion's (re)discovery it has attracted a great deal of research interest and a large number of alternative explanations (reviewed in Krekelberg and Lappe, 2001; Nijhawan, 2002). The first explanation proposed was that of motion extrapolation: the visual system predicts the position of a moving object based on its prior trajectory to overcome processing delays and achieve co-ordinated movement (Nijhawan, 1994). This theory fails to explain why the effect persists when the flash initiates the movement cycle, disappears when the flash occurs at the end of the movement cycle and reverses when the ring changes direction at the moment the flash occurs (in all cases, only subsequent motion appears relevant in producing an effect). Perhaps the most common explanation has been in terms of processing delays for the flashed stimulus relative to the moving one (e.g. Baldo and Klein, 1995). However, the illusion emerges in contexts where a processing delay is not obvious (e.g. when a stationary stimulus continuously changes colour relative to a flashed colour patch; Sheth, Nijhawan, and Shimojo, 2000) and is not reduced by giving the flash a temporal head start in a flash initiated paradigm (Eagleman and Sejnowski, 2000). A third explanation suggests that information about the moving stimulus is integrated in a time window following the flash before determination of the subsequent conscious experience (Eagleman and Sejnowski, 2000). However, this account fails to deal with findings that the effect is modified when the nature of the flash changes (e.g. for luminance manipulations; Patel, Ogmen, Bedell, and Sampath, 2000). There are other accounts and variants, but it is fair to say that none currently explain all the data. What emerges clearly from these studies, however, is that the relationship between physical events and mental sequencing is complex, and that while often difficult to interpret, illusory effects offer clues to the
solutions employed by the brain in differing contexts. The forthcoming experimental chapters describe a new illusion that will hopefully prove equally stimulating and contentious.
Chapter 2. Saccadic chronostasis

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 position. Take the situation in which we glance at our watch or at a large digital clock like those commonly found in railway stations. For a short period, the second hand appears to have stopped; then, suddenly, it ticks on. It is as if the image of the clock were frozen for just a moment following a saccade. This phenomenon is of intuitive interest as an experience that most people recognise, yet has been little discussed in the scientific literature.

There have been attempts to link the stopped clock phenomenon to temporal illusions occurring under static viewing conditions. Rose and Summers, for example, demonstrated that for a sequence of four rapidly presented square light patches, the first square was perceived to be on screen for longer than was actually the case (Rose and Summers, 1995). In their standard paradigm, in which the latter three squares were presented for 666 ms each with a 100 ms inter-stimulus interval, the first square needed to be presented for only around 450 ms to appear of equal duration to the second. A similar effect was obtained across manipulations of inter-stimulus interval, stimulus size and stimulus contrast. However, this illusion occurs under conditions of continuous fixation, in contrast to the classic stopped clock sensation; no attempts have been made to generalise it to the post-saccadic situation.

When judgements of a temporal nature have been studied in the context of saccades, illusory biases have again emerged. In an early report, subjects were asked to judge whether a horizontal sinusoidal test grating presented for 5 ms arrived before, during or after a 6° saccade of approximately 30 ms duration. (Volkmann and Moore, 1978). Stimuli were presented in the area traversed by the saccade, at a variety of contrasts relative to an equiluminant background. For stimuli presented after the onset of the saccade (with only the “during” and “after” responses available) two
observers showed a strong bias towards judging the stimulus to have arrived during the saccade. They were still as likely to respond “during” as “after” 200 ms after the saccade had ended. For the single observer tested with stimuli also occurring prior to the saccade (and additionally given the “before” response option) these stimuli were also judged to have occurred during the saccade more often than would be expected, while the previous pattern was repeated for stimuli arriving after the saccade. Oddly, while stimuli arriving shortly before the saccade were judged to occur during it, those actually arriving during the saccade were typically judged to have arrived before it, preventing the tidy conclusion that times of occurrence for these stimuli were drawn inwards towards the saccadic event.

More recently, Deubel, Irwin and Schneider (1999) have obtained temporal biases under similar conditions. In two experiments, they had subjects make either reactive saccades to a peripheral target (left or right) or delayed saccades one second after a central cue that indicated direction (6° in both cases). An open circle appeared on screen for 20 ms at a time ranging from 450 ms before the saccade to 250 ms after it. The circle was located at one of three locations: the initial fixation point, the saccade target point, or the opposite point (the alternative saccade target). Six subjects judged whether their gaze had been on the central fixation point or the saccade target point when the circle appeared. Subjects showed shifted response curves when the circle appeared at the saccade target; they often incorrectly felt that they were already looking at the saccade target even when the circle appeared well before their saccade. The effect was less marked when the circle appeared opposite the target, and nearly absent when it appeared at the initial fixation point. However, in these experiments the whole psychometric curve was simply shifted towards negative circle-saccade asynchronies. Subjects showed no tendency to claim that they were still looking at the central fixation point when the circle appeared after their saccade, a result that would complement the over-attribution of post saccadic stimuli to the “during” category in Volkmann and Moore’s experiments. It seems possible that differences in the nature of the question
asked and the response categories available to subjects may explain these anomalous findings.

The results of the previous two studies appear somewhat contradictory and are challenging to interpret given their methodological differences. Additionally, their relevance to the stopped-clock illusion is not immediately apparent, given that these studies have dealt with temporal order judgements relating to the instant of occurrence of very briefly presented stimuli. When the clock stops we feel that a period of time has been stretched out, not that an instantaneous time marker has been shifted. This is not to deny that the underlying mechanisms might be common, but rather to suggest that alternative methodologies may yield results that are easier to interpret.

Only recently have attempts been made to look directly at the effects of saccadic eye movements on the perceived duration of a stimulus presented for a prolonged duration following the completion of the saccade, a situation analogous to that in which the stopped clock illusion is typically experienced. Brown and Rothwell (1997) asked subjects to make self-paced 60° saccades towards a numerical LED display that mimicked a digital second hand. Subjects judged whether the time for which they saw the first digit was greater or less than the time that subsequent digits were displayed. In reality, all digits were displayed for one second. They found that when saccades began just before a switch of digit (meaning that the eyes alighted on their target around about or just after a change) subjects tended to judge the first digit to have been displayed for longer than subsequent digits. This finding represents a simple laboratory demonstration of the ubiquitous stopped clock illusion. Hereafter, this effect will be referred to as saccadic chronostasis.

The methodology employed by Brown and Rothwell has the virtue of being extremely true to the conditions under which saccadic chronostasis is typically experienced. However, it does not allow for the quantification of effect size (the degree to which the first digit is “stretched out”) and, therefore, a systematic examination of factors that might influence the
illusion. To this end, a new methodology is introduced here in which the change of counter digit is triggered by the saccade in a consistent manner. Brown and Rothwell speculated that the perception of the first digit viewed was being extended back in time following a saccade. Assuming that this backward extension was towards the beginning of the saccade or some specific pre-saccadic event, this would imply that the size of the saccadic chronostasis illusion ought to be influenced by the size of the saccade. Experiment 1a addressed this question.

Experiment 1a

Methods.

Participants. Initially, 10 subjects completed the experiment. Using the variance of their data, a power calculation was carried out to estimate the sample size required to detect an effect of 60 ms as a planned comparison between the long and short saccade conditions ($\alpha = 0.05$, $\beta = 0.2$, power = 0.8). Consequently 20 further subjects were tested, giving a total of 30 subjects (18 male, mean age 28.2, SD 7.4).

Apparatus. Subjects sat before a 14" CRT colour monitor refreshing at 60 Hz. Eye to screen distance, which varied between conditions (25 or 66 cm) was maintained using an adjustable chin rest. Horizontal eye movements were recorded using AC electro-oculography (D150 amp: Digitimer; band pass filtered 0.032-30 Hz) and sampled at 200 Hz. Electrodes were placed on the outer canthus of each eye. Stimuli were black on a white background, subtending approximately 0.5°. They consisted of a cross and/or a digital counter, initially set to “0” and counting through the digits “1” to “4”. The experiments were controlled by a PC interfaced with a 12 bit A/D card (National Instruments DAQ 1200).
Design. A repeated-measures 2 x 2 factorial design was employed. The first factor eye status compared a voluntary saccade to constant fixation (the control). The second factor screen distance manipulated saccade size (22° or 55°); control conditions were conducted with the counter at matched eccentricity (±11° or ±27.5°). Four blocks of data were recorded in each condition. For counterbalancing purposes, screen distance order was counterbalanced across subjects, while blocks were alternated (control then saccade) for the eye status factor. Hence each subject received four repetitions of a control block followed by a saccade block at one screen distance, then at the other.

Procedure. In the saccade conditions, subjects fixated a cross on one side of the screen, initiated the trial with a mouse 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” when the saccade had travelled one fifth of the distance to target. The “1” remained on screen for 400-1600 ms; subsequent digits (“2”, “3”) remained on the screen for 1 s each, culminating in the appearance of a “4”. Figure 2.1 shows a schematic of this process. Subjects indicated whether the time they saw the “1” was longer or shorter than that for the subsequent digits. Saccade start/end points were calculated automatically using a velocity criterion; difference values between sample n and sample n-3 were compared to thresholds based on background signal noise. Trials where the first saccade recorded did not exceed 90% of the total distance recorded (summed across all detected saccades) were excluded on line and repeated immediately. Additionally, trials were rejected if the algorithm was unable to generate realistic start/end points for technical reasons, such as an excessively noisy signal or an attempt to saccade during the initial period assigned for background noise assessment. In control (constant fixation) trials, subjects simply fixated a “0” at equivalent eccentricity that changed to become the judged digit (“1”) 500 ms after the subject’s mouse key press. Direction of saccade (saccade conditions: left to right and vice versa) or

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1 60 ms represented a conservative estimate of the time difference between the long and
position of the counter (control conditions: left or right) alternated every trial.

![Image: Schematic of experimental procedure (22° saccade).]

In all conditions, the computer controlled the duration of the first digit by a modified binary search (MOBS; Tyrrell and Owens, 1988) procedure that “homed in” on a single matched estimate (low boundary 400 ms, high boundary 1600 ms, initial presentation random 800-1200 ms). The MOBS procedure worked by maintaining two boundaries. On each trial, the subject’s response determined whether the value that was currently being tested replaced the low or high boundary. If they responded “less than” the current value replaced the lower boundary and vice versa. The next value was then selected as the midpoint between the two updated boundaries. Checks ensured that boundaries could be pushed out again in response to persistent responding (i.e. following a lapse of judgement). Details of the Visual Basic procedure used to implement the MOBS in this and later experiments are presented in Appendix A. Details of general programming methods used to ensure accurate timing are presented in Appendix B. The search terminated following five reversals of choice by the subject, concluding the block and yielding a single estimate equal to the midpoint of the final boundaries. Blocks were consequently of variable length, typically 6-20 trials excluding those rejected. In the saccade conditions, each estimate was corrected post hoc to match the time the “1” was on screen following target foveation by subtracting the average time the eye was in motion short saccades employed.
following the triggered change of digit (averaged across all four blocks). The experiment took around one hour to complete.

Statistical analyses. Standard parametric tests (repeated-measures ANOVAs and t-tests) were used to assess differences in the dependent variable (mean of four matched estimates derived from the MOBS procedure) across conditions. Alpha was set at 0.05. For validation purposes, alternative estimates were obtained in some conditions using logistic regression. Logistic regression is a technique that can be used to fit a sigmoidal regression line to data for which the dependent variable is a dichotomy. A logit (log \(e\) odds) transformation is used to provide a continuous linear variable to which a regression line can be fitted. The resultant regression equation can be used to determine the value of the independent variable at which each of the original dichotomous dependent variable’s outcomes are equally likely to occur. Given the equation:

\[
(1) \ln(\text{odds}) = a + bx
\]

Where \(a\) is the intercept and \(b\) the slope, then rearranging to solve for \(x\) (the independent variable) for a probability of 0.5 (equivalent to odds of 1 or \(\ln(\text{odds})\) of 0) gives:

\[
(2) x = -a/b
\]

Trial-by-trial data were entered into a logistic regression analysis with first digit presentation time as the independent variable and response (0 or 1 for “less than” or “more than”) as the dependent variable.² Where the regression was significant, the point of subjective simultaneity (equivalent to the estimated time matched to one second derived from the MOBS) was

² Strictly speaking, logistic regression assumes the independence of each observation, an assumption that is violated because the MOBS procedure creates dependencies between prior responses and subsequent presentation durations. This violation should only affect significance levels for the fit, however, not derived statistics (i.e. the point of subjective simultaneity), although see Kaernbach (2001) for a discussion of possible bias.
calculated in the above manner. These values could be adjusted to represent the time the “1” was on screen following target foveation in the same manner as for those derived from the MOBS.

Results and discussion.

Saccade characteristics. Across all subjects, the 22° saccades took an average of 72 ms to complete (range 54-105 ms), while the 55° saccades lasted an average of 139 ms (range 106-214 ms). Hence the average difference in completion times between the two conditions was 67 ms. These values are reasonable for saccades of these sizes (Collewijn, Erkelens, and Steinman, 1988). Within subjects, saccades were made with fairly reproducible time courses (mean standard deviation across saccades 9 ms for the short saccades, 16 ms for the long saccades). Subjects often exhibited small corrective saccades typically beginning 80-180 ms after their first saccade landed, a commonly reported finding. Based on manual inspection of saccade traces, such corrective saccades occurred 75 percent of the time for long saccades and 69 percent of the time for short saccades, a difference that was small but significant (t = 3.042, df = 29, p = 0.005). In all cases, time estimates were corrected to the point at which the large initial saccade landed.

Time estimates. Figure 2.2 shows the mean corrected time estimates across subjects in all four conditions. These estimates will commonly be referred to as subjective seconds, being the time matched to subsequent one-second intervals. Subjects thought they had seen the initial digit for one second when their gaze had been on the target for only 880 ms (22° saccade condition) or 811 ms (55° saccade condition). Control conditions gave very different values that were close to veridical time perception. A two-factor (2

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3 These authors conducted a thorough analysis of four subjects’ eye movement data for voluntary saccades recorded with a scleral sensor coil. They found the linear function duration = 2.7 x amplitude + 23 ms provided an excellent fit for symmetrical saccades across the midline with amplitudes of up to 50 degrees, with duration increasing with a small additional non-linear component in the range 50-80 degrees.
repeated measures ANOVA revealed significant main effects for both eye status ($f = 92.48$, $df = 1, 29$, $p < 0.001$) and screen distance ($f = 6.915$, $df = 1, 29$, $p = .014$). It failed to show an interaction, probably because of the slightly lower value of the control subjective second in the near screen ($55\degree$) condition ($f = 2.079$, $df = 1, 29$, $p = 0.16$). However, given that testing the difference between the two saccadic conditions was the primary experimental goal, the planned comparison between them was still conducted, revealing a significant difference ($t = 2.553$, $df = 29$, $p = 0.016$). Interestingly, there was an almost exact agreement between the extra time taken for the eyes to move over the longer distance (67 ms) and the resultant differences in subjective seconds (880-811 = 69 ms), suggesting that the illusion of saccadic 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. This finding supports the suggestions made by Brown and Rothwell (1997) and extends them to explicitly link the size of the saccadic chronostasis illusion with the size of the preceding saccade.

**Validation of the MOBS technique.** The MOBS technique used here has the advantage that it arrives at an estimate for a subjective second in
relatively few trials. However, the procedure is based on heuristic reasoning and lacks a solid foundation in statistical theory (Treutwein, 1995). As a step towards validating its use, the results obtained from each subject using the mean average of four MOBS blocks were compared to those obtained by subjecting the same data to logistic regression analyses. Initially, this analysis was conducted for both saccading conditions. Regression lines were significant for 20/30 subjects in the long saccade condition and 21/30 subjects in the short saccade condition, permitting the derivation of subjective seconds by this alternative method for around two thirds of the sample. An example logistic regression line is plotted for one subject’s data in the short saccade condition in figure 2.3. Given that a number of subjects’ data could not be fitted in this way, it is clear that logistic regression had a
higher trial requirement than MOBS, from which four separate estimates had been derived. This was true even given that the tendency of the MOBS procedure to deliver many trials near to the subjects' decision thresholds ought to minimise the number of trials required (Rosenberger and Grill, 1997). Traditional non-adaptive approaches such as the method of constant stimuli would probably require many more data points.

For the subjects whose data was well fitted, subjective seconds derived using the two techniques' estimates were compared. In the long saccade condition, the correlation between the mean MOBS estimate and that derived from logistic regression was an impressive 0.986, yielding almost identical mean subjective seconds of 764 and 766 ms respectively. For the short saccade condition, the correlation was even higher at 0.995, with subjective seconds of 875 and 876 ms. The two techniques therefore appear to yield very similar results. Note that while subjective seconds are once again smaller in the long saccade condition for these sub-samples, data across the conditions is less suitable for comparison given that the groups were not identical, with only 15 subjects contributing data to both.

Relevance of corrective saccades. It has been noted that the proportion of trials on which corrective saccades were made was not identical between the long and short saccading conditions. It is possible that corrective saccades (or their absence) may have some part to play in the experience of saccadic chronostasis. Because logistic regression can be employed post-hoc, it permitted a weak test of this hypothesis. Those trials on which subjects had made corrective saccades were entered into a separate logistic regression. Within a given condition, estimates were derived if a subject:

1) Produced significant regressions both for all trials taken together, and for only those trials on which corrective saccades had been made.
2) Failed to make corrective saccades on at least 10 percent of trials.
After applying these criteria, data was available for comparison from 9 subjects in the long saccade condition and 14 subjects in the short saccade condition. In their complete data sets, these subjects produced corrective saccades on 73 percent and 72 percent of trials respectively. If the presence of corrective saccades influenced saccadic chronostasis, it seems reasonable that excluding those trials on which only a single saccade occurred from the regression analysis ought to alter the resultant subjective second estimates. In fact, no such difference could be detected. For the long saccade condition, mean subjective seconds were 765 ms with all data included and 762 ms when only trials with corrective saccades were considered. For short saccades, these values were 853 ms and 855 ms. Neither difference was significant. Although this post-hoc analysis is far from ideal (the manipulation would be expected to have a limited influence and probably lacked power, making a failure to obtain a difference difficult to interpret) it does at least suggest that the presence of later corrective saccades makes little difference to the experience of saccadic chronostasis.

Experiment 1b

The results of Experiment 1a appeared to demonstrate that saccadic chronostasis occurred as a result of eye movements that provided new detailed information about a visual object. This information was judged to have been gained at a time some 50 ms prior to the beginning of the saccade, giving the impression of a stretched percept. However, it is possible that it was not the eye movement itself, but rather the related uncertainty about the time of onset for the “1” that gave rise to the illusion. Saccadic chronostasis might not be saccadic at all, in the sense of being directly tied to the production of a movement, but rather be a special case of time uncertainty about objects in shifting visual scenes. To test this theory, Experiment 1b attempted to produce chronostasis in a situation where, rather than the eyes moving to a counter, the counter moved towards the point of fixation.
Methods.

Participants. 10 subjects completed Experiment 1b (9 male, mean age 30.5, SD 7.8). 9 had previously participated in experiment 1a.

Apparatus. The equipment and visual stimuli used were identical to those employed in Experiment 1a, with eye to screen distance set to 60 cm. Eye movement data were not recorded for off-line analysis, but the eye position signal was regularly checked to ensure that the eyes remained fixated.

Design. A repeated-measures design was employed with two conditions: a moving counter condition (MC; counter traverses 24° with a velocity 240° per second) and a stationary counter control condition (SC; similar to the constant fixation control conditions in Experiment 1a, but with fixation at ± 12° eccentricity). Four blocks of data were recorded in each condition. Order was counterbalanced across subjects with one block from each condition completed in turn (i.e. MC-SC-MC-SC-MC-SC-MC-SC or vice versa).

Procedure. In the moving counter condition, subjects fixated a cross on one side of the screen. A target “0” was displayed on the other side of the screen, separated from the cross by 24° of visual angle. Subjects initiated the trial with a mouse key press. 1000 ms later, the cross disappeared and the target “0” changed to a “1”, then moved rapidly to the point of fixation, covering the entire distance in 100 ms (six screen refreshes). The “1” remained on screen for 400-1600 ms; 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” at the fixation position was longer or shorter than that for the subsequent digits. Eye position was monitored at 10 Hz during the 1000 ms fixation period, then as often as computer processing speed permitted during counter movement. Trials
where the eyes wandered more than 4.8° from fixation were excluded on
line and repeated immediately. In control trials, subjects simply fixated a
“0” at equivalent eccentricity that changed to become the judged digit (“1”) 500 ms after the subject’s mouse key press. Initial fixation (right or left) alternated on each trial.

In all conditions, the computer controlled the duration of the first digit using a MOBS procedure (low boundary 400 ms, high boundary 1600 ms, initial presentation random 800-1200 ms, five reversals to terminate). In the moving counter condition, estimates were corrected post hoc to match the time the “1” was on screen after it had arrived at the fixation point by subtracting the time it had been in motion (100 ms). The experiment took around 30 minutes to complete.

![Figure 2.4](image-url)

**Figure 2.4.** Mean time (ms) matched to one second when a counter moves 24° to fixation compared to when it remains at fixation throughout. Error bars show standard deviations.

Results and discussion.

Figure 2.4 shows the mean corrected time estimates across subjects in the two conditions. In both conditions, subjects’ judgements are close to the correct value of 1000 ms. In fact, there is a non-significant trend towards longer subjective seconds in the moving counter condition ($t = 1.364$, $df = 9$, $p = 0.206$). These data provide no support for the hypothesis that saccadic chronostasis is a by-product of temporal uncertainty about objects in moving scenes. In Experiment 1a short saccades yielded effect sizes in excess of 100 ms for eye movements taking around 70 ms. Here, counter movement at a speed approaching that of saccades that lasted for 100 ms yielded no such effect. In fact, the trend was in the opposite direction. The failure to obtain a difference is unlikely to result
from a lack of experimental power, which was 0.91 to detect a 100 ms difference at \( \alpha = 0.05 \). It therefore seems likely that the experience of saccadic chronostasis is directly dependent upon the production of an eye movement.

Experiment 1c

In Experiment 1a subjects never reported being aware of the change of digit (0 to 1) that occurred during their voluntary saccade. In analysing the data, it was assumed that no information about the counter was available during eye movement, such that duration estimation could only begin when the eyes alighted on their target. Subjective seconds were therefore corrected to represent the period the "1" was displayed starting from the moment the eyes landed. However, it is possible that subjects were in fact able to perceive the mid-saccadic counter change and to use it as a cue to initiate time judgements. This would invalidate the correction method employed in Experiment 1a, resulting in an underestimation of subjective seconds. As a potential artefact, this problem cannot completely explain the results of Experiment 1a. The sizes of the effects obtained were greater than the durations of the eye movements by around 50 ms, implying that perception of the first digit was extended back to before the eyes had even moved. Nonetheless, it may have contributed to the reported effect size, and in particular may have been responsible for the differences obtained for saccades of varying extent. To control for this possibility, Experiment 1c was designed to assess the influence of the time of mid-saccadic digit change upon saccadic chronostasis. This change was triggered either early or late during a large saccade and the resulting subjective seconds compared. If the counter change did provide information useful for time judgements, subjective seconds (once corrected to the time of saccadic landing) should be shorter in the conditions in which triggering occurred early on, with the magnitude of this difference being similar to the time difference between the two trigger points.
Methods.

Participants. 10 subjects (9 male, mean age 31.4, SD 7.6) completed Experiment Ic. 5 had previously participated in experiment la.

Apparatus. The equipment and visual stimuli used were identical to those employed in Experiment 1a with the following changes. Eye to screen distance was set to 24 cm. Horizontal eye movements were recorded using DC electro-oculography (7A22 amp: Techtronix; low-pass filtered at 100 Hz) and sampled at 200 Hz.

Design. A repeated-measures design was employed with two conditions both involving a 55° saccade. In the early trigger condition, counter change from “0” to “1” occurred when the saccade had travelled one fifth of the way to target. In the late trigger condition, this change occurred after four fifths of the distance had been covered. Four blocks of data were recorded with each block containing trials randomly interleaved from both conditions.

Procedure. Subjects fixated a cross on one side of the screen, initiated the trial with a mouse key press then made a voluntary 55° saccade to a target “0” on the other side. Eye movement triggered a change of digit to a “1” which remained on screen for 400-1600 ms. 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. Direction of saccade (left to right and vice versa) alternated every trial. Saccade start/end points were calculated and trials rejected as per Experiment 1a. Because signal noise was the primary cause of saccade rejection in previous experiments and the DC EOG amp used here had a relatively high low-pass filter setting an optional digital filter was incorporated prior to start/end point detection. A second
order 30 Hz low-pass Butterworth filter was applied to the eye data in both forward and reverse directions to prevent any phase shift. Filter coefficients were derived using commercial software and implemented by the experimental software as described in the supporting literature (Matlab: the Maths Works Inc.) The filter was used for two subjects.

Both conditions were tested within a single block. Two independent MOBS procedures controlled stimuli presentation time, one for each condition (low boundary 400 ms, high boundary 1600 ms, initial presentation random 800-1200 ms, five reversals to terminate). Trials were drawn from each condition randomly until one MOBS had terminated, after which they were drawn exclusively from the other condition to complete the block. Blocks were typically 12-40 trials in length excluding those rejected. Estimates were corrected to saccade landing time as per Experiment 1a. The experiment took around 30 minutes to complete.

Results and discussion.

Saccade characteristics and triggering times. Across all subjects, saccades took an average of 153 ms in the early trigger condition (range 124-184 ms) and 152 ms (range 122-178 ms) in the late trigger condition. Corrective saccades were once again regularly observed. DC recording allowed better estimation of saccade extents, with first saccades covering an average of 51.2° of visual angle in both conditions. In the early trigger condition, the change of digit occurred on average 33 ms after saccade initiation (plus an average of 8.3 ms due to screen refresh rate limitations). With late triggering, the change occurred after an average 118 ms plus refresh, meaning that the digit was actually displayed for an average of 85 ms longer in this condition.

Time estimates. Figure 2.5 shows the mean corrected time estimates across subjects in both conditions. There is a small but non-significant trend for subjective seconds to be increased with later triggering ($t = 0.324$, $df = 9$, $p$
= 0.754). The magnitude of this effect was far smaller than that of the experimental manipulation (an 85 ms increase in display time) implying that subjects did not perceive the moment of counter change and use this event as a marker to initiate their temporal judgements. It therefore seems unlikely that such an explanation can account for the differences observed in the magnitude of saccadic chronostasis between long and short saccades found in Experiment 1a. Some caution must be exercised, however, as power for this study was respectable (0.71 to detect an 85 ms difference at $\alpha = 0.05$) but failed to tightly constrain type II experimental error.

Experiment 1d

Experiment 1a suggested that the post-saccadic percept was predated to approximately 50 ms before saccade initiation, perhaps implying that some pre-motor event served as a marker. It is possible, however, that the illusion of saccadic chronostasis is not uniquely related to movement of the eyes per se, but occurs because of related shifts of attention. A number of lines of evidence suggest that people shift the locus of their visual attention at around the time their eyes move (Rizzolatti, Riggio, and Sheliga, 1994). For example, there is evidence for enhancement of stimuli processing in the direction of an upcoming saccade in both immediate identification/classification tasks and when these stimuli act as primes for subsequent targets (Godijn and Pratt, 2002; Rorden and Driver, 1999). While the premotor theory of attention remains contentious (particularly
regarding the specifics of any causal relationship between covert attention and saccade programming) an attention-shifting account of saccadic chronostasis needs to be addressed. It is unlikely that an isolated shift of covert attention would be responsible for the results of Experiment 1a. Saccadic chronostasis was dependent upon saccade size, and the temporal qualities or attention redistribution are unlikely to precisely mirror those of eye movements (Sperling and Weichselgartner, 1995). Nonetheless, attention shifts may be crucial when occurring in the context of saccades. Given that the timing of a shift of attention cannot be measured in the same way as for an eye movement, Experiment 1d was designed to indirectly assess the influence of attention by having subjects deliberately direct their covert attention to the counter well in advance of making a saccade. It is well known that correctly cued shifts of covert attention improve reaction time to visual stimuli (Posner, 1980). Subjects therefore completed a reaction time task on alternating trials to assess whether they really were allocating attention as required. If the attention shift that usually precedes an eye movement is important for saccadic chronostasis, it would be predicted that an early reallocation of attentional resources should affect the illusion. Two obvious possibilities are that such reallocation might enhance effect size (if the earlier than usual attention shift is used as a marker for predating) or destroy saccadic chronostasis (if the illusion depends upon the typical attention-saccade coupling).

Methods.

Participants. 12 subjects’ data were included in Experiment 1d (10 male, mean age 32.8, SD 9.3), another two having been excluded because they failed to redirect attention appropriately (as indicated by the RT measure). 9 had previously participated in experiment 1a.

Apparatus. The equipment used was identical to that employed in Experiment 1a except that eye to screen distance was set to 60 cm. An
additional stimulus (a black leftward or rightward facing arrow) was used in the saccade plus attention condition.

*Design.* A repeated-measures design was employed with three conditions: a saccade condition (12° saccade made from central fixation outwards), a saccade plus attention condition (as the saccade condition, but with a prior shift of covert attention to the counter) and a constant fixation control condition (similar to the constant fixation control conditions in Experiment 1a, but with fixation at ± 12° eccentricity). Order was counterbalanced across subjects, with one block completed from each condition in turn. Four blocks of data were recorded in each condition.

*Procedure.* The saccade condition alternated between two types of trials: *Time estimation trials* and *RT trials.* In the time estimation trials, subjects fixated a cross at the centre of the screen, initiated the trial with a mouse key press then made a voluntary 12° saccade to a target “0” to the left or right. Eye movement triggered a change of digit to a “1” which remained on screen for 400-1600 ms. 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. Direction of saccade (leftwards or rightwards) alternated every time estimation trial. Saccade start/end points were calculated and trials rejected as per Experiment 1a. In the RT trials, subjects fixated a central cross, above which the words “RT trial” were clearly displayed, and again initiated the trial with a mouse key press. After a random delay of 500-1000 ms a target “0” appeared 12° to the left or right. Subjects made a speeded saccade to the target, with RT recorded as the time at which their eyes had travelled one fifth of the distance to target (2.4°). Errors were recorded if eye movements of this extent or greater were made in the wrong direction. Target direction (left or right) was randomly generated on each trial. The target “0” did not change, and no time judgements were required.
In the saccade plus attention condition, time estimation trials were identical to those in the saccade condition except that subjects were told to make a deliberate covert shift of visual attention to the target “0” before initiating the trial. In RT trials, an arrow was displayed to the right or left of fixation (randomly selected on each trial) and subjects directed their visual attention in the cued direction before initiating the trial. Subjects were truthfully informed that the cue was completely non-predictive, but that they should nonetheless direct their attention as indicated. In the control condition, subjects simply fixated a “0” at equivalent eccentricity that changed to become the judged digit (“1”) 500 ms after the subject’s mouse key press, then made time judgements as per time estimation trials in the saccade condition. Initial fixation (right or left) alternated on each trial.

In all conditions, the computer controlled the duration of the first digit for time estimation trials using a MOBS procedure (low boundary 400 ms, high boundary 1600 ms, initial presentation random 800-1200 ms, five reversals to terminate). Estimates were corrected to saccade landing time as per Experiment 1a. The experiment took around 60 minutes to complete.

Statistical analyses. Standard parametric tests were used where normality and homogeneity of variance assumptions held. For repeated measures ANOVAs with three levels, sphericity violations were controlled using the Greenhouse-Geisser correction when $\epsilon$ was below 0.7 and the Huynh-Feldt correction when Greenhouse-Geisser $\epsilon$ was above 0.7 (Howell, 1997).

Results and discussion.

Saccade characteristics. Across all subjects, saccades took an average of 47 ms in the saccade condition (range 39-54 ms) and 46 ms (range 37-53 ms) in the saccade plus attention condition. Corrective saccades were common.

Reaction Time. Two subjects were replaced because they failed to show the predicted RT improvement for correctly cued compared to incorrectly cued
trials. Figure 2.6 shows reaction times and error rates in the saccade plus attention condition (when target appearance was correctly or incorrectly cued) and in the saccade condition (no attention cue) for the 12 subjects whose data was included in the time estimate comparisons. For reaction time data, ANOVA revealed a significant difference across the three conditions ($f = 17.542$, corrected df = 2, 20, $p < 0.001$). Reaction time was lower on trials where attention was directed to the position of the upcoming target or when no early allocation of attention was made compared to those on which it was directed to the wrong side of space ($t = 4.108$, df = 11, $p < 0.01$; $t = 5.367$, df = 11, $p < 0.001$). A similar pattern emerged for error data. These data suggest that subjects were successful in allocating their attention in the required direction. Although RT was as low when no requirement existed to direct attention as when attention was correctly cued, subjects completed the former trials in a separate block; this finding may therefore result from the generally increased task demands of the saccade plus attention blocks.

Another possibility is that inhibition of return arose during the attention-allocation trials. The term inhibition of return was originally used
to describe slowed responses to stimuli presented at the position of an earlier attention-engaging cue (Posner and Cohen, 1984). In general, it arises at the position of exogenous (peripheral) cues that capture attention in an automatic manner, with slowing observed for stimuli presented in excess of 300 ms after such cues. The endogenous, central cue used here may still be relevant, however, because these cues can yield inhibition of return under specific circumstances: when a saccade is made or planned in the cued direction (Rafal, Calabresi, Brennan and Sciolto, 1989). The RT effects of endogenous attention allocation strategies and inhibition of return appear to operate in an additive fashion when assessed together (Berger and Henik, 2000) with cued attention benefits being rather greater than inhibition of return deficits. Subjects were clearly quicker when their attention was correctly allocated compared to false cueing within the same block, but this enhancement may have been the net result of an ongoing attention allocation policy in concert with inhibition of return. Hence no advantage was seen relative to the blocks without attention allocation requirements, because here the (less marked) attention benefit was completely cancelled out by inhibition of return. However, it is not clear why subjects should have planned a saccade based on the endogenous cue. Inhibition of return does not typically arise for endogenous cues, showing that saccade planning is not mandatory, although the experimental context (the requirement for a saccadic response) probably exerted some influence.

This speculative inhibition of return account suggests that subjects might have initially planned a saccade based upon the endogenous cue, then instigated an attention allocation policy that maintained spatial attention in the required direction despite competing inhibitory tagging. The original Posner methodology employed a simple RT task rather than a two-choice RT task like that used here in order to dissociate spatial attention from motor preparation. In a key press task, motor preparation might have a similar and therefore confounding effect on reaction times. However, the current experiment was intended to address the possibility that the mandatory attentional shift preceding a saccade might operate as a time
marker in chronostasis. It is therefore premised on a necessary linkage between shifts of attention and saccades, such that a motor preparation account of the RT data is equivalent to a spatial shifting account in terms of achieving the desired experimental manipulation. The key point is that both demonstrate that the temporal relationship between the hypothesised pre-motor attentional time marker and saccade onset was substantially altered.

Figure 2.7. Mean time (ms) matched to one second following a saccade of 12° with/without an early shift of attention or during continuous fixation. Error bars show standard deviations.

A significant difference emerged across all conditions ($f = 14.457$, corrected df = 2, 17, $p < 0.001$) reflecting reliable effects for both saccade and saccade plus attention conditions relative to control (Fisher’s LSD: $t = 4.262$, df = 11, $p = .001$; $t = 3.922$, df = 11, $p = .002$). The difference between the saccade and saccade plus attention conditions was not reliable, suggesting that the instruction to subjects to make an early shift of covert attention prior to initiating the trial had little effect on the resultant experience of saccadic chronostasis. Given that RT results show that this instruction did result in successful reallocation of attentional resources these data would imply that the attention shift that typically precedes an eye movement is not used as a marker for backdating. Otherwise an increase in effect size ought to have been observed in the saccade plus attention condition. In fact the opposite trend was observed, but not to the extent that might be expected if altering the coupling between attention shift and saccade destroyed the illusion.
Clearly there are difficulties making bold statements on the basis of negative results. Power exceeded 0.99 to detect a complete disruption of saccadic chronostasis in the saccade plus attention condition (effect size of 150 ms, \( \alpha = 0.05 \)) but it is unclear how much disruption or enhancement of the illusion might be expected and/or be of theoretical interest. Based on this data, any effect of less than 90 ms would result in \( \beta > 0.05 \). It therefore seems reasonable to conclude only that the attention manipulation used here (the conscious early deployment of covert visual attention to a specific spatial location) did not: 1) Completely destroy saccadic chronostasis, or 2) Enhance it in a way commensurate, ms for ms, with the change in the time of the attention shift.

The data presented in figure 2.7 may appear to contradict the major finding from Experiment 1a; that saccadic chronostasis increases with saccade size. Here, a saccade of only 12° produces an effect midway between those reported earlier for saccades of 22° and 55° respectively. However, inter-subject variability is high for this task (note the high subjective seconds for very large saccades in Experiment 1c and the high standard deviations of estimates in all experiments). Figure 2.8 shows data for only those 9 subjects who participated in both Experiment 1a and Experiment 1d. Results continue to support a linear effect size scaling with saccade duration.

General discussion
Results are reported here from four experiments exploring the phenomenon of saccadic chronostasis. In Experiment 1a, subjects made voluntary saccades of two sizes: 22° and 55°. The size of the illusion was found to increase in a manner precisely scaled to saccade duration, with an additional constant of around 50 ms. Experiment 1b controlled for the possibility that the effect might relate to uncertainty about the onset time of objects in rapidly changing visual displays rather than being specific to objects fixated by eye movements. No evidence was found for this interpretation. Experiment 1c assessed the degree to which the results of Experiment 1a might have been artefactually enhanced by perception of the onset of the judged digit early on in a saccade. No evidence was found for such enhancement. Finally, Experiment 1d attempted to explore the role of pre-saccadic shifts of visual attention in saccadic chronostasis. No evidence was found that intentionally altering the timing of an attention shift affects the illusion.

Taken together, these experiments provide a strong case for assigning a key role to eye movements in the generation of saccadic chronostasis. Whatever processes drive the illusion appear to be tightly linked to eye movement generation rather than just the visual conditions such eye movements produce. They also appear to be sensitive to critical parameters of eye movements (i.e. movement time). There is also good reason to believe that saccadic chronostasis, as described here, is the major cause of the ubiquitous stopped clock illusion. Under static viewing conditions, estimates for the duration of the first interval in a chain of three intervals were quite accurate. This is in contrast to results obtained for trains of stimuli separated by brief blank periods (Rose and Summers, 1995). It is interesting to speculate on the reasons for these differing results. In Rose and Summers' experiments the stimuli were light against a darker background, of shorter duration (600 or 667 ms) and always separated by at least 100 ms. However, what is clear is that the control conditions employed in the present experiments were much closer to the typical experience of
watching a clock. Under these conditions, large shifts away from veridical time perception only occurred following a saccade.

Brown and Rothwell's suggestion that the onset of the post-saccadic image is being predicted to around the time the saccade begins remains extremely plausible given the current findings (Brown and Rothwell, 1997). Such an interpretation makes sense when viewed in the light of other processes occurring around the time of eye movements. Saccades are extremely rapid eye movements and produce a retinal image that is both difficult to resolve and contains powerful motion transients. It is therefore striking that we experience no sensation of either blurred vision or movement despite making many thousands of saccades every day. It is well established that visual thresholds are raised around the time of saccades, an effect that primarily occurs for stimuli of low spatial frequencies analysed via the achromatic channel (Burr and Morrone, 1996; Sato and Uchikawa, 1999). Despite the contention that this may be the by-product of mechanical shearing forces that bend photoreceptors (Castet, Jeanjean, and Masson, 2001) it is widely accepted that such saccadic suppression results from active central inhibition (Ross, Morrone, Goldberg, and Burr, 2001). This inhibition appears to selectively affect the magnocellular pathway and has been recorded in neurons from the middle temporal and middle superior temporal areas of the primate brain (Thiele, Henning, Kubischik, and Hoffmann, 2002). Saccadic suppression, in combination with the speed-related smearing of high spatial frequency visual components and subsequent masking by post-saccadic images, goes a long way towards explaining our lack of visual awareness and sense of visual stability during saccades. It poses an interesting question, however, for temporal judgements that relate to the condition of a visual scene during a saccade. What state should be assigned to the visual world during the perceptual gap implied by saccadic suppression? The results of saccadic chronostasis experiments strongly suggest that the brain fills this gap with the post-saccadic visual scene. Consequently, percepts resolved following an eye movement (such as
the "1" in the present experiments) are judged to have been present for longer than is actually the case.

An explanation that incorporates mechanisms of saccadic suppression has the advantage of casting some light upon the constant (around 50 ms) found in saccadic chronostasis experiments. In the present experiments, the post-saccadic image was backdated to a moment prior to the initiation of eye movement. Saccadic suppression also begins before the saccade with a similar time course. Indeed, the same can be said of other illusory perceptions occurring around the time of saccades, such as the recently reported "compression" of visual space. Here, targets flashed at various locations in the spatial and temporal vicinity of a saccade are spatially misperceived in the direction of the saccade target (Ross, Morrone, and Burr, 1997). Again, the effect is found prior to saccade initiation. Interestingly, it is largely dependent upon the presence of a visual reference immediately following the saccade and does not occur when the visual reference is available prior to the saccade (at the actual time of stimulus presentation) but is subsequently extinguished (Lappe, Awater, and Krekelberg, 2000). It is therefore suggested that the pre-motor event to which the post-saccadic percept is backdated may well relate to the initiation of saccade-dependent central manipulations of visual input.

The role of attention in saccadic chronostasis is a challenging question to address. Shifts of spatial attention take time, but the function relating their duration to distance traversed may be flat (Sperling and Weichselgartner, 1995) and when gradients are inferred they differ from those derived for saccades (Tsai, 1983). However, any shift would be expected to precede the initiation of a saccade, so the movement-size related effects found in Experiment 1a could imply backdating to this event. Experiment 1d did not suggest that voluntarily shifting attention early on disrupted the illusion, or enhanced it in manner consistent with using the attention shift as a marker for backdating the post-saccadic stimuli, but such a voluntary reallocation of attention may not be the whole story. Many researchers have made a theoretical distinction between voluntary and
automatic attentional processes, although the two may interact in a complex manner (Pashler, Johnston, and Ruthruff, 2001). Only voluntary attention shifts were addressed here, and the manipulation may not have prevented reflexive attention-related processes from occurring with their usual time course. In general, attention shifts appear to be mandatory just before a saccade, overriding endogenous attention allocation (Hoffinan, 1998; Schneider and Deubel, 2002). It is possible, if rather counter intuitive, that such a reallocation would occur even when attention had previously been directed to the same location (i.e. that attention would be transiently withdrawn then reassigned prior to saccade execution). The simplest explanation of our data is that eye movements are crucial, with attention shifts playing little part in saccadic chronostasis. However, it remains possible that the illusion depends on some interaction of movement and attention, or that similar illusions could be obtained for attention shifts in the absence of movement. It would, for example, be interesting to combine a duration judgement like that employed here and by Rose and Summers (1995) with a task that correctly or incorrectly cued spatial attention to the location of the first stimulus. Subsequent stimuli could appear in the same or spatially separate locations.

Clearly the experiments presented here have only begun to describe the phenomenon of saccadic chronostasis. A number of pertinent questions remain, some of which will be taken up in later chapters. Firstly, the time estimation procedure used here is undoubtedly a difficult task that yields noisy estimates for individual subjects. Good results have been obtained by averaging across subjects, but the question of potential individual differences cannot be addressed (not all subjects showed the effect, but this could easily reflect the relatively limited amount of data each subject contributed). Secondly, these experiments used voluntary saccades, but saccades made under different circumstances (e.g. reactive) may yield different results. A third question relates to the range of saccade sizes explored (12° to 55°). Would the saccade-duration-related results of Experiment 1a generalise to saccades beyond these limits? The explanation
presented here makes much of the temporal relationship between effect size and saccade duration, but other factors covary with saccade duration (e.g. extent, peak velocity) and may be more relevant, with dissociation occurring outside of the range tested here. Fourthly, if time judgements are incorrect following a saccade, what happens in the case of moving stimuli, for which misperceiving time of occurrence might imply misperception of position? Although much remains to be seen, a cautious explanation has been proposed here in which the post-saccadic image is used to backfill the perceptual blank caused by a saccade, thus extending its perceived duration and giving rise to saccadic chronostasis. This interpretation leads to a fifth question relating to the inevitability of such a process. Does the brain fill the perceptual gap with the post-saccadic percept under all stimulus conditions? It is this question that is addressed in Chapter 3.
Chapter 3. Image discontinuities destroy saccadic chronostasis

In Chapter 2 it was demonstrated that saccadic chronostasis occurs when rapid eye movements are made to an initially poorly resolved stationary visual object which, once fixated, maintains its appearance for a period approaching one second. Under these circumstances, the object is judged to have been perceived in its resolved perceptual state for longer than is actually the case, as if the onset of the post-saccadic image had been predated to before eye movement was initiated. When judgements of a temporal nature are to be made about items presented near to or during a saccade, the brain is faced with a challenge. Visual information is degraded, such that the state of the visual world becomes uncertain. It appears that the brain solves this problem by making the heuristic assumption that the post-saccadic image is accurate for the duration of the saccade. This is not a trivial or obvious solution. The post-saccadic visual scene might reasonably be dated from the point of saccade termination when its contents can be known with certainty. In developing this explanation of the data on saccadic chronostasis, it is useful to briefly review what is known about the construction and maintenance of representations in the visual scene.

In scenes viewed under static visual conditions, low-level visual features must be segmented to produce candidate objects (e.g. figure-ground segmentation in Gestalt demonstrations). Such a process must occur early in visual processing, allowing the formation of more complex object representations for further analysis. The manner in which basic features are combined remains controversial, particularly given the cortical separation of areas involved in their processing (Treisman, 1999). Two methodologies widely employed to investigate the automatic (as opposed to attention demanding) nature of such “binding” processes are visual search (search for a single target among distracters) and demonstrations of illusory conjunctions (the incorrect binding of features like colour and form into a non-existent percept). In both cases, initial enthusiasm for the crucial role of attention in combining location-coded features into objects has been
tempered to suggest some degree of pre-attentive grouping with subsequent attention-dependent elaboration (Wolfe and Cave, 1999). Similarly, strong claims regarding the attention-demanding nature of even very simple visual encoding (derived from inattentual blindness paradigms) are giving way to a perspective in which attention operates upon “proto-objects” (Driver, Davis, Russell, Turatto, and Freeman, 2001). What seems clear is that following the deployment of attention in some form perceptual objects are created and subsequently analysed in a unitary manner. Multiple points of movement can be successfully tracked in a visual scene, but when they are combined to form a single flexible object attention cannot be deployed to them individually and tracking performance is degraded (Scholl, Pylyshyn, and Feldman, 2001). Short-term visual memory also appears to operate at an object level. Following the rapid presentation of an array of either different coloured vertical bars or black bars of different orientations subjects can hold around four features (colours or orientations) in memory for future comparison. However, if bars varying in both colour and orientation are used, subjects can hold four objects, equivalent to eight features, in memory. As more features are added (size, presence/absence of a gap) it is still possible to maintain four object representations despite the proliferation of features, suggesting that visual working memory capacity is best understood in terms of coherent objects (Luck and Vogel, 1997).

An interesting finding emerging in recent years is that while our phenomenological visual experience is rather complete, the representation we construct about objects in particular scenes appears to be quite sparse. This finding first became apparent in studies of eye movements. The initially plausible idea that visual images from different fixations are overlaid or combined in a detailed integrative visual buffer has not been well supported. Rather, it appears that a limited number of visual objects may be maintained, along with a higher order schema representing the gist of the scene as a whole. This picture is exemplified by a study conducted by Irwin and Andrews (1995). They displayed six different coloured letters in two rows above and below fixation during the reaction time period of a
reactive (left/right) saccade task. Following the saccade, the position of one of the letters was cued for recall. They found that form (letter) and colour information were maintained in a correlated form when recall was successful, with a capacity of three to four such items (integrated objects) and better performance near the saccade target. A second experiment used ten dark grey letters and either one or two saccades, with the letters displayed until the onset of the second saccade in the two saccade condition. Memory capacity did not significantly increase in this condition, despite a doubling of the time available for viewing and the addition of a second fixation, but the pattern of position-related performance enhancement changed such that facilitation shifted to straddle both the fixated locations.

Cross-saccadic memory has also been assessed using change detection tasks. Here, it has become increasingly clear that not only shifts of visual targets in unstructured scenes, but displacements of complete and realistic visual scenes or specific components of them often go unnoticed during a saccade (Currie, McConkie, Carlson-Radvansky, and Irwin, 2000). However, such "change blindness" is not limited to cross-saccadic images. Any visual event that induces visual noise capable of foiling or confusing low-level transience detectors, be it caused by a brief blanking between images, a blink, or even "mudsplashes" that leave the crucial retinal location unaffected, will cause observers to miss substantial changes in the visual scene (O'Regan, Deubel, Clark, and Rensink, 2000). Such changes appear obvious once discovered or pointed out. These effects are evident in even the most natural situations. In one study, subjects often failed to spot that a stranger asking for directions turned into a different person when workmen walked between them carrying an interposing door (Simons and Levin, 1997).

These findings are clearly relevant to understanding what happens to visual representations across saccades. When our eyes move we are faced not only with the problem of image motion (discussed in Chapter 2 in relation to saccadic suppression) but with the related issue of space constancy. How is it that objects appear stable in extrinsic space despite
their translation across the retina? Early theories suggested that afferent sensory information from the eyes and/or a copy of the movement commands issued to them (efference copy or corollary discharge) might compensate for saccades, cancelling out the resultant shift of position (Sperry, 1950; Von Holst and Mittelstaedt, 1950). Alternative, ecologically motivated approaches suggested that the unique quality of retinal information arising from a saccade could unambiguously inform the brain that a saccade is occurring, effectively by-passing the problem (Gibson, 1966). However, efferent and afferent information, individually or together, are not precise enough to mediate our perfect sense of visual stability, and experimental evidence suggests that they do not fully compensate for eye displacement during static viewing in unstructured visual scenes. Regarding the pure retinal solution, tapping on the canthus of the eye produces a striking sensation of spatial shift; here, retinal information clearly fails to allow the brain to recognise this displacement for what it is and ignore it. Hence traditional explanations of space constancy face substantial problems (Bridgeman, Van der Heijden, and Velichkovsky, 1994). Such difficulties, in combination with the data reviewed above relating to the limited scope of cross-saccadic representations, have lead to new formulations emphasising the role of reference objects in the post-saccadic visual scene that are assumed by the brain to have maintained their spatial position (Currie et al, 2000). Evidence suggests that visual objects near to the saccade target that are present immediately following saccade completion are adopted as stable anchor points, with visual space reconstructed around them (Deubel, Bridgeman, and Schneider, 1998). Hence detailed information need only be maintained across saccades about a few such objects; failure to detect them within a critical temporal and spatial window most likely causes the system to fall back on less accurate extra-retinal cues (i.e. sensory inflow/outflow).

This viewpoint emphasises a neural assumption about the spatial continuity of key objects in the visual scene. Such an assumption seems somewhat analogous with that proposed to underlie saccadic chronostasis in Chapter 1, i.e. that the counter maintains its post-saccadic form across the
saccade. Numerous experiments have demonstrated that shifts of a saccade target often go unnoticed if implemented during a saccade. Such shifts may be up to a third of saccade extent when fixating lights in the dark (Prablanc and Martin, 1992) but at some point the shift becomes noticeable, as if the system rejects its standard assumption and falls back on other cues. Although the assumption suggested to underlie chronostasis relates to the form (appearance) of an object, not its position, the review of object-based notions presented above suggests that such features of objects are likely to be bound up for short-term internal representation (e.g. object files; Kahneman, Treisman, and Gibbs, 1992). Experiment 2a emerged directly from this reasoning: Might disrupting the perceived positional stability of an object break assumptions about the continuity of its appearance? To this end, a double-step paradigm was employed in which the saccade target was systematically shifted during the saccade, with the hypothesis that the perception of such a shift would result in a disruption of saccadic chronostasis.

Experiment 2a

Methods.

Participants. Initially, 10 subjects completed the experiment. Using their data, a power calculation was carried out to estimate the sample size required to detect an effect of 110 ms as a bonferroni-corrected comparison between the two conditions that showed greatest variability in their difference scores (familywise $\alpha = 0.05$, $\beta = 0.2$, power = 0.8). The required sample of 22 subjects (16 male, mean age 30.8, SD 7.4) was selected from a total of 26 subjects who competed the experiment; four subjects were rejected because their data did not permit a valid subjective second estimate to be derived in all conditions (see below).
**Apparatus.** Subjects sat before a 14” CRT colour monitor refreshing at 60 Hz. Eye to screen distance was maintained at 38 cm using an adjustable chin rest. Horizontal eye movements were recorded from the left eye using an infra-red eye tracker (Microguide 1000 spectacles, low-pass filtered at 40 Hz) and sampled at 200 Hz. Stimuli were white on a black background, subtending approximately 0.5°. They consisted of a cross and/or a digital counter, initially set to “0” and counting through the digits “1” to “4”. The experiments were controlled by a PC interfaced with a 12 bit A/D card (National Instruments DAQ 1200).

**Design.** A repeated-measures design was employed with four conditions. The first three conditions all involved saccades of 20° in which the counter either remained stationary (*no shift* condition), shifted and was perceived to do so (*perceived shift* condition) or shifted but was judged to have remained stationary (*unperceived shift* condition). The fourth *control* condition involved constant fixation with the counter at matched eccentricity (±10°). For the three conditions involving saccades, trials were interleaved within a single block. Control trials were presented in separate blocks. Four control blocks and four saccade blocks were completed. Block order was counterbalanced across subjects and alternated (control then saccade then control etc. or vice versa). Where logistic regression was not significant to produce a time estimate in one or more conditions, two additional blocks (one control, one saccade) were completed. If regressions still failed to reach significance, the subject was rejected and replaced.

**Procedure.** In saccade blocks, subjects fixated a cross on one side of the screen, initiated the trial with a mouse key press that caused a target “0” to appear on the other side, then made a voluntary saccade towards it. Eye movement triggered a change of digit to a “1” when the saccade had travelled one fifth of the distance to target. On some trials, the target was horizontally shifted at this point. The “1” remained on screen for 400-1600

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1 110 ms was an effect size estimate based on a 60 ms saccade plus the 50 ms constant
ms; subsequent digits ("2", "3") remained on the screen for 1 s each, culminating in the appearance of a "4". Figure 3.1 shows a schematic of this process. Subjects indicated whether the time they saw the "1" was longer or shorter than that for the subsequent digits, and also whether they felt the target had shifted during their eye movement (responding yes or no).

Figure 3.1. Schematic of experimental procedure for a hyper-metric shift trial.

Trials were drawn randomly with equal probability from three pools. Trials from the first pool involved no counter shift. For these trials, the duration of the "1" was controlled by a MOBS procedure (low boundary 400 ms, high boundary 1600 ms, initial presentation random 800-1200 ms, five reversals to terminate). Once this MOBS had terminated, no further trials were generated from this pool. Trials from the second and third pools involved counter shifts in hypo- or hyper-metric directions respectively. Here, the extent of the shift was controlled by a MOBS procedure that responded to the subject's binary decision about whether a shift had occurred (one per pool: low boundary 0°, high boundary 9°, initial presentation random 1.5-7.5°, five reversals to terminate). In this manner, shift extents were maintained close to the subject's threshold of shift detection. The duration of the "1" was not controlled by a MOBS; rather, it was generated randomly from a uniform distribution in the range 400-1600 ms. Following termination of either MOBS, trials continued to be generated

derived from Experiment 1a
from the relevant pool, with the shift extent set equal to the threshold estimate derived at MOBS termination plus an integer value randomly generated in the range -2 to +2. The block ended when the MOBS in each of the three trial pools had terminated. Trials were allocated to the three saccadic experimental conditions post hoc, with trials from the first pool providing data exclusively to the no shift condition, and trials from the second and third pools being divided into perceived shift and unperceived shift conditions according to subjects’ responses.

Saccade start/end points were calculated automatically using a velocity criterion; difference values between sample n and sample n-3 were compared to thresholds based on background signal noise. Trials where the first saccade recorded did not exceed 50% of the total distance recorded (summed across all detected saccades) were excluded on line and repeated immediately. This value was lower than for experiments reported in Chapter 2 because of the potential for large (9°) shifts of saccade target giving rise to substantial corrective saccades. In control (constant fixation) trials, subjects simply fixated a “0” at equivalent eccentricity that changed to become the judged digit (“1”) 500 ms after the subject’s mouse key press. Direction of saccade (saccade conditions: left to right and vice versa) or position of the counter (control conditions: left or right) alternated every trial.

_blocks were of variable length, typically 6-20 trials for control blocks and 20-60 trials for saccade blocks (excluding those rejected). Subjective second estimates were derived using logistic regression in all cases. In the saccade conditions, each estimate was corrected post hoc to match the time the “1” was on screen following target foveation by subtracting the average time the eye was in motion following the triggered change of digit (averaged across all four blocks and all three saccadic conditions). The experiment took around one hour to complete.

Statistical analyses. Details of the logistic regression technique used to derive subjective second estimates are presented in Chapter 2 (Experiment 1a). In timing research, Weber ratios are commonly used as a measure of
subjects' sensitivity to temporal changes (Ferrara, Lejeune, and Wearden, 1997). Where the p = 0.5 value on the psychophysical curve (here the logistic regression function) represents the mean value matched to a given standard interval (here one second), giving an estimate of bias, the Weber ratio gives an estimate of response variability. Standard Weber ratios are calculated by taking the difference between the p = 0.75 and the p = 0.5 values on the psychophysical curve to yield a difference limen, then dividing by the p = 0.5 value to normalise.\(^2\) Higher values represent increased variability in timing responses. The conditions used here vary in expected mean values (saccadic chronostasis causes a bias) such that the standard Weber ratio normalisation procedure would tend to overestimate variability in conditions yielding an illusory effect relative to control. For this reason, the difference limen was divided by the p = 0.5 value from the control condition in all cases. The resulting Weber ratios were averaged across subjects in order to determine whether the experimental manipulations affected the difficulty of the subsequent time judgement task. Where MOBS procedures also culminated in a temporal estimate (in the control and no shift conditions) an alternative measure of timing variability was obtained by calculating for each subject the standard deviation across the four MOBS-derived values.

Estimates of subjects' thresholds for detecting a counter shift in hypo- and hyper-metric directions were produced by averaging MOBS-derived values for trials from the appropriate pool across the four saccadic blocks. Standard parametric tests (repeated measures ANOVAs and bonferroni-corrected t-tests) were used to assess differences across conditions with alpha set at 0.05 and appropriate corrections made for sphericity violations (as per Experiment 1d).

Results and discussion.

\(^2\) The p = 0.75 point is derived according to the equation \(x = (\ln(3)-a)/b\), where \(a\) is the intercept and \(b\) is the slope.
Saccade characteristics and thresholds for shift detection. Across all subjects and saccadic conditions, saccades took an average of 62 ms (range 44-77 ms). Corrective saccades were regularly observed, and were of substantial size in the conditions in which the target shifted. Infra-red recording tended to produce cleaner signals than electro-oculography, and despite its more limited range was linear within the ±10° average extents used here (some non-linearity was evident for large hyper-metric target shifts). First saccade extents were similar across the three saccadic conditions, covering an average of 18.5° in the no shift and unperceived shift conditions and 18.4° in the perceived shift condition. In the no shift condition, subjects incorrectly reported the presence of a target shift on 8.7% of trials (range 0-38.9) suggesting a fair degree of perceptual uncertainty. In the two shift conditions, thresholds for perceiving target displacement were significantly lower for hypo-metric than hyper-metric saccades (2.1° verses 2.9°, t = 4.651, df = 21, p < 0.001). This finding is interesting and probably relates to the tendency of the saccadic system to undershoot targets. A hypo-metric target shift will leave the target closer to the initial post-saccadic fixation point than a hyper-metric shift, such that a theory implicating fixation-to-target distance as a major factor in shift detection might predict a difference in the opposite direction to that found here. On the other hand, if the system expects to undershoot the target and virtually never overshoots it, a hypo-metric shift that causes it to overshoot will be a very obvious cue for error detection. This reasoning would predict the result obtained here. Previous research comparing change detection for shifts of entire rich visual scenes and/or the specific saccade targets contained within them showed both trends; shift detection increased with fixation-to-target distance for entire scenes but decreased with it for objects within scenes (Currie et al, 2000). The current data is for target shifts within a fixed frame (the computer screen) so the findings are consistent. These authors explained their result in terms of an interaction between two systems mediating change detection, one relying on fixation to target distance and the other on altered spatial relations between key elements of the scene.
Figure 3.2. a. Average logistic regression plots for four conditions involving a saccade of 20° with no target shift, a perceived target shift or an unperceived target shift, or simply constant fixation (control). Mean Weber ratios and standard deviations are shown below each. Plots were produced by combining the mean time matched to one second in each condition (providing the horizontal offset) and the mean Weber ratio (providing the slope). b. Mean time (ms) matched to one second in each condition. Error bars show standard deviations.

**Time estimates.** Figure 3.2a shows the Weber ratios obtained to estimate variability when performing the temporal matching task in the four conditions. It is apparent that the Weber ratio is much lower in the control condition, suggesting that subjects were able to perform the temporal discrimination task more accurately when no saccade preceded it. This finding was confirmed statistically, with a significant ANOVA ($f = 11.397$, corrected df = 3, 59, $p < 0.001$) and significant post-hoc pairwise comparisons between the control condition and each of the other three conditions. There was little evidence, however, that the shifting counter manipulation affected the variability of subjects’ timing performances and therefore task difficulty for the three conditions in which time judgements were made after a saccade. Although there was a slight trend for Weber
ratios to increase in the two shift conditions these differences failed to reach significance. In the no shift and control conditions, an alternative measure of timing variability was available: the standard deviation of subjects’ four MOBS-derived estimates. To test the equivalence of the two measures, they were correlated across subjects, yielding significant correlation coefficients of 0.87 in the no shift condition and 0.92 in the control condition. Hence, as expected, higher variability between MOBS-generated values was associated with a higher Weber ratio, suggesting that trends in variability across conditions derived with either method would have been similar. This result is revisited in Experiment 2b.

Figure 3.2b shows the mean corrected time estimates across subjects in all four conditions. In this experiment, subjects showed a general tendency to underestimate the length time the “1” was on screen; even in the control condition, subjective seconds were somewhat low and differed significantly from 1000 ms ($t = 2.488$, df = 21, $p = 0.021$). There are a number of possible partial or complete explanations for this result. Firstly, reference (one second) periods conformed precisely to a multiple of screen refresh time, whereas the initial test period did not, and consequently would have suffered from related variability. This effect would be small, however ($\approx 8$ ms); note that it does not effect the crucial experimental comparisons, as it occurs in all conditions. Secondly, although the precise timing task used here is novel, individual differences in time perception tasks are commonly observed (Ryan and Robey, 2002) and the sample may have been biased by chance. More interestingly, the effect may relate to that obtained by Rose and Summers (1995) and discussed in Chapter 2. Whereas the saccadic chronostasis experiments reported here previously used black digits on a white background, the reverse was true for the current experiment. Given that Rose and Summers obtained their results using squares of light this change may have been a relevant one (although the sizes of the two effects remains quite different).

Another possibility is that this effect represents an example of the time order error, a tendency for the order of presentation to affect
performance in many kinds of comparison task. For temporal judgements, the time order error is considered positive when the first of two stimuli is overestimated relative to the second (as here) and negative when it is underestimated. Both results have been obtained in previous research, with some dependency upon the absolute duration of the stimuli (Allan, 1979). Although a gap between the two stimuli is typically employed, the effect has also been obtained for adjacent stimuli (Allan and Gibbon, 1994). The time order error was much discussed in the classical timing literature and is often considered to be quite unpredictable and capricious. This may explain its appearance here but not in earlier chronostasis experiments. The most comprehensive theory of the time order error published thus far suggests that comparisons are made using representations that are based upon the entire sequence of presented stimuli, not just those presented in the current trial (Hellstroem, 1985). Series adaptation levels are differentially affected by the first and second stimuli in a trial as a function of sensation weights, which vary across changes in factors such as inter-stimulus-interval and stimulus duration. It is not immediately apparent why these variables should have changed in the current experiment compared to previous ones, although the method used here involves a non-systematic presentation order for stimulus durations and random variation in their magnitudes, factors that would be expected to effect the time order error. No formal analysis is attempted here.

Regarding the critical experimental comparisons, a substantial saccadic chronostasis effect is once again obtained when the counter remains stationary throughout the saccade, replicating the results obtained in Experiments 1a and 1d. The size of this effect is large (822 ms compared to the 1000 ms reference digits) for a saccade of only 20° (62 ms) but the low control estimate should perhaps be borne in mind. The results of the perceived shift and unperceived shift conditions are striking: saccadic chronostasis is largely absent when a noticeable target shift occurs, and is substantially reduced when a shift of similar extent goes unnoticed. Statistical analysis confirmed a reliable difference across the four groups (f
Post-hoc pairwise comparisons revealed a significant difference between the no shift condition and all other conditions but no other reliable differences. Hence saccadic chronostasis occurs under standard (stationary counter) conditions relative to all the other conditions tested here, with no significant effect in the shifting counter conditions relative to control. This pattern of subjective seconds across the four conditions is dissociated from that obtained for Weber ratios. It therefore seems that increased task difficulty is a feature of post-saccadic time judgements in general rather than being a correlate of processes underlying saccadic chronostasis itself.

These findings provide strong support for the experimental hypothesis that undermining the perceived positional stability of the counter would disrupt saccadic chronostasis. Based on the results of Experiments 1a to 1d an account was proposed in which the brain assumes that the post-saccadic image accurately reflects the visual scene throughout the saccade and consequently predates the contents of that image to just prior to saccade onset. Evidence has been reviewed suggesting that the visual system tracks a limited number of integrated perceptual objects across changing visual scenes and uses them as anchors to maintain external spatial continuity. In the case of space constancy, the assumption of positional stability for target objects is broken when they are shifted outside a critical region, and other mechanisms are employed for localisation. Given the integrated nature of visual objects, spatial shifts might reasonably imply discontinuities in other features of an object. The results presented here suggest that a spatial shift disrupts not only the standard assumptions underlying space constancy but also the assumption of form constancy that has been proposed to underlie saccadic chronostasis. Conscious awareness of target shifts may be linked to assumptions of object constancy, but are unlikely to mirror them exactly. This would explain the partial (non-significant) effect observed when target shifts occur but are not reported. Before moving on to discuss the possible implications of such an account, however, it is necessary to address alternative explanations of the present data. It is possible that shifting the
counter in this experiment had other effects on observers that caused disruption of saccadic chronostasis, such that the results obtained here were not specific to a shift of the saccade target object. Experiment 2b tested one such potential effect.

Experiment 2b

In Experiment 2a, saccadic chronostasis was disrupted when the counter was shifted mid saccade, the degree of this disruption reflecting subjects’ awareness of such a shift. Before concluding that the target shift itself was critical, it is necessary to address an account of these results focussing on the arousal generated by an unexpected visual event. When subjects perceive a counter shift, they may be surprised or distracted by this event, and such distraction may underlie their failure to experience saccadic chronostasis. Inserting an alternative distracting visual event that does not impinge on the positional stability of the counter but appears at an identical time would test such an account. To this end, Experiment 2b employed alphabetic characters appearing mid-saccade in the vicinity of the counter to determine if their distracting effects would disrupt saccadic chronostasis.

Methods.

Participants. 10 subjects completed Experiment 2b (7 male, mean age 29.4, SD 7.5). 9 had previously participated in experiment 2a.

Apparatus. The equipment and stimuli used were identical to those employed in Experiment 2a with the addition of lower-case characters randomly selected from the entire alphabet in a font size identical to that employed for the digits of the counter (10 point).

Design. A repeated-measures design was employed with four conditions. The first three conditions all involved saccades of 20° to a stationary
counter. Saccade detection was used to trigger simply the first digit change (no distracter condition) or to additionally cause a random alphabetic character to appear either 1° (near distracter condition) or 3° (far distracter condition) from the counter. The fourth control condition involved constant fixation with the counter at matched eccentricity (±10°). For the three conditions involving saccades, trials were interleaved within a single block. Control trials were presented in separate blocks. Four control blocks and four saccade blocks were completed. Block order was counterbalanced across subjects and alternated block by block.

Procedure. In saccade blocks, subjects fixated a cross on one side of the screen, initiated the trial with a mouse key press that caused a target “0” to appear on the other side, then made a voluntary saccade towards it. Eye movement triggered a change of digit to a “1” when the saccade had travelled one fifth of the distance to target. On some trials, a random lowercase alphabetic character appeared to the left or right of fixation at this point. The “1” remained on screen for 400-1600 ms; 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 were drawn randomly with equal probability from the three conditions involving a saccade. In trials from the no distracter condition, only the counter was present in the visual display. In trials from the near distracter and far distracter conditions, a letter appeared 1° or 3° from the counter respectively. Letter position (left or right of the counter) was chosen randomly on each trial. In each condition, the duration of the “1” was controlled by a separate MOBS procedure (low boundary 400 ms, high boundary 1600 ms, initial presentation random 800-1200 ms, five reversals to terminate). Once a given MOBS had terminated, no further trials were generated from that condition. The block ended when the MOBS in each condition had terminated. Saccade start/end points were calculated and trials rejected as per Experiment 2a. In control (constant fixation) trials, subjects
simply fixated a “0” at equivalent eccentricity that changed to become the judged digit (“1”) 500 ms after the subject’s mouse key press. Direction of saccade (saccade conditions: left to right and vice versa) or position of the counter (control conditions: left or right) alternated every trial.

Blocks were of variable length, typically 6-20 trials for control blocks and 20-60 trials for saccade blocks (excluding those rejected). Subjective second estimates were produced by taking the average of the four MOBS-generated values; saccade condition estimates were corrected as per Experiment 2a. The experiment took around one hour to complete.

Results and discussion.

Saccade characteristics. In the no distracter condition, first saccades took an average of 66 ms (range 48-99 ms) and covered an average 18.4° of visual angle. With near distracters, these values were 64 ms and 18.3°, while far distracters yielded average saccades taking 65 ms and covering 18.1°. Corrective saccades were common.

Time estimates. Figure 3.3 shows the mean corrected time estimates across subjects in all four conditions. As in the previous experiment a rather low control condition subjective second is evident. However, this value did not differ significantly from 1000 ms so will not be discussed further here. In Experiment 2a, variability of time judgements was estimated using Weber ratios and did not vary significantly across the three saccadic conditions, which all displayed increased variability relative to the control. Mean Weber ratios were shown to correlate highly with standard deviations across MOBS-derived values. Consequently, the mean of standard deviations across the four MOBS values was employed here as an equivalent measure. While the control value was once again low relative to the other conditions, the difference was less striking than in Experiment 2a and the ANOVA failed to reach significance (control = 75, no distracter = 101, near distracter = 104, far distracter = 88). Returning to Figure 3.3, saccadic chronostasis is
evident in all three saccadic conditions, which yielded remarkably similar estimates. ANOVA revealed a significant difference across conditions ($f = 6.749$, corrected $df = 3, 27$, $p = 0.002$). Post-hoc pairwise comparisons showed significant or marginally significant differences between the control condition and each of the saccading conditions, which did not differ from one another (control versus no distracter: $t = 3.5$, $df = 9$, $p = 0.04$; near distracter: $t = 3.22$, $df = 9$, $p = .063$; far distracter: $t = 3.724$, $df = 9$, $p = .028$).

Despite a single result being only marginally significant in the presence of a bonferroni correction these data strongly suggest that saccadic chronostasis arises regardless of novel onset events in the visual scene occurring at the time of a saccade. It therefore seems unlikely that the distracting nature of the manipulation employed in Experiment 2a was the crucial factor in undermining the illusion. Rather, it appears that something specific to the sudden perturbation of objects appearing both pre- and post-saccadically caused this disruption. The only question outstanding in the interpretation of these two experiments relates to the equivalence of the distraction caused in each. Clearly this is a difficult point to address, given the rather vague nature of any arousal-based account of Experiment 2a. The stimuli in Experiment 2b were designed to appear in positions similar to those to which the counter shifted in Experiment 2a. They were of similar size and identical colour/luminance. Subjects reported that targets that

![Figure 3.3](image-url)
shifted and distracters that appeared suddenly were similarly surprising and off-putting. Neither type of manipulation increased the difficulty of the subsequent temporal-estimation task compared to standard saccadic chronostasis conditions, as indexed by Weber ratios in Experiment 2a or standard deviations of MOBS termination points in Experiment 2b. All in all it seems likely that their distracting effects were quite similar, implicating the counter shift itself as the crucial factor.

Experiment 2c

The data from Experiments 2a and 2b suggest that specific visual events occurring mid saccade disrupt saccadic chronostasis. If the counter is perceptibly displaced then the illusion is dispelled, whereas the appearance of distracting characters does not affect it, suggesting that the perceived spatial continuity of the counter is crucial. However, it is possible that the counter is not unique in this respect. The evidence reviewed at the beginning of this chapter suggests that around four objects can be tracked across display changes, so while a change in the display as a whole (the appearance of distracting characters) does not influence saccadic chronostasis, spatial shifts of other objects present in the pre-saccadic scene might do so. Representations of such objects would probably be established in a manner similar to that employed for the saccade target itself. Indeed, space constancy studies have demonstrated that other objects near the saccade target can be preferentially used as stable anchor points when the saccade target itself is briefly blanked at the time of post-saccadic fixation (Deubel, Bridgeman, and Schneider, 1998). It has also been shown that even when the saccade target object remains stationary, relative shifts of other objects are often perceived (Currie et al, 2000). To test the suggestion that spatial displacement of any object stored in visual short term memory would disrupt saccadic chronostasis, a random letter was presented just above the counter and, on a subset of trials, shifted to a noticeable extent.
Methods.

Participants. 10 subjects completed Experiment 2c (6 male, mean age 26.0, SD 5.2). 7 had previously participated in experiment 2a.

Apparatus. The equipment and stimuli used were identical to those employed in Experiment 2b except that the lower-case characters (randomly selected from the entire alphabet) were displayed in a font size a little larger than that employed for the digits of the counter (16 point compared to 10 point). This change was made to increase their discriminability and salience, given that they were presented at a peripheral position.

Design. A repeated-measures design was employed with three conditions. The first two conditions both involved saccades of 20° to a stationary counter with an irrelevant letter displayed above it. Saccade detection was used to trigger simply the first digit change (no shift condition) or to additionally displace the letter to the left or right (shift condition). The control condition involved constant fixation with the counter at matched eccentricity (±10°). For the two conditions involving saccades, trials were interleaved within a single block. Control trials were presented in separate blocks. Four control blocks and four saccade blocks were completed. Block order was counterbalanced across subjects and alternated block by block.

Procedure. In saccade blocks, a cross was displayed on one side of the screen, while a target “0” was visible on the other side. A random letter was displayed 2° above the “0”. Subjects initiated the trial with a mouse key press then made a voluntary saccade towards the “0”. Eye movement triggered a change of digit to a “1” when the saccade had travelled one fifth of the distance to target. On some trials, the letter shifted 3° to the left or right at this point, a shift designed to be noticeable while leaving the letter close enough to the post-saccadic fixation point to be easily perceived. The “1” remained on screen for 400-1600 ms; 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 were drawn randomly with equal probability from the two conditions involving a saccade. In trials from the no shift condition, the letter remained stable above the counter throughout. In trials from the shift condition, it was displaced to the left or right, with direction chosen randomly on each trial. In either condition, the duration of the “1” was controlled by a separate MOBS procedure (low boundary 400 ms, high boundary 1600 ms, initial presentation random 800-1200 ms, five reversals to terminate). Once a given MOBS had terminated, no further trials were generated from that condition. The block ended when the MOBS in both conditions had terminated. Saccade start/end points were calculated and trials rejected as per Experiment 2a. In control (constant fixation) trials, subjects simply fixated a “0” at equivalent eccentricity that changed to become the judged digit (“1”) 500 ms after the subject’s mouse key press. Direction of saccade (saccade conditions: left to right and vice versa) or position of the counter (control conditions: left or right) alternated every trial.

Blocks were of variable length, typically 6-20 trials for control blocks and 12-40 trials for saccade blocks (excluding those rejected). Subjective second estimates were produced by taking the average of the four MOBS-generated values; saccade condition estimates were corrected as per Experiment 2a. The experiment took around forty minutes to complete.

Results and discussion.

Saccade characteristics. In the no shift condition, first saccades took an average of 66 ms (range 46-96 ms) and covered an average 18.8° of visual angle. In the shift condition these values were 65 ms (range 38-93 ms) and 19.0° respectively. Corrective saccades were again regularly produced.
Time estimates. The pattern of variability of time judgements was similar to that produced in Experiments 2a and 2b. The mean standard deviation across MOBS values was lower in the control condition relative to the saccadic conditions (control = 78, no shift = 120, shift = 125) but this difference was not reliable in an ANOVA. Figure 3.4 shows the mean corrected time estimates across subjects in the three conditions. The control estimate is once again quite low, continuing a trend found throughout this chapter using white stimuli on a black background, but as in Experiment 2b it did not differ reliably from 1000 ms. Subjective seconds were lower in the no shift condition, a typical demonstration of saccadic chronostasis, but were close to control values in the shift condition, suggesting that saccadic chronostasis was disrupted when the spatial continuity of an irrelevant object located close to the counter was broken. This finding implies that the hypothesised assumption underlying backward extension of a post-saccadic percept can be challenged by the displacement of any sufficiently salient object in the visual scene, not just the one appearing at fixation. However, statistical support for the trends observed in this Experiment is limited, so strong conclusions cannot be drawn. An ANOVA used to test differences across the three conditions was not significant. Despite this finding, the specific experimental hypothesis that shifting the letter might disrupt saccadic chronostasis was tested as a planned comparison between the shift and no shift conditions and did reveal a significant difference ($t = 2.441$, $df = 9$, $p = 0.037$). Power was certainly an issue in this experiment. For the contrast exhibiting the greatest variability (control versus no shift conditions) it was only at 0.4 to detect the
expected 110 ms effect ($\alpha = 0.05$, Fisher’s LSD correction, equivalent to no correction following a significant ANOVA). 28 subjects would have been required to reach a power of 0.8.

**General discussion**

The experiments reported here were designed to search for and investigate specific conditions under which saccadic chronostasis does not occur. In Experiment 2a, the illusion was obtained under typical conditions, but no effect was found when the counter was displaced to a noticeable degree in the middle of a saccade. An illusion of reduced magnitude was found when such a counter shift went unnoticed, suggesting that conscious awareness may be correlated with but not exactly mirror whatever process suppressed saccadic chronostasis in this experiment. Experiment 2b employed distracting stimuli appearing mid saccade to test an arousal account of these data. Such stimuli did not disrupt saccadic chronostasis. To the extent that the degree of arousal/distraction was equivalent in the two experiments, it can be concluded that the disruption observed in Experiment 2a was the specific result of a continuously present object in the visual scene (in this case the saccade target object) suffering spatial displacement. Some evidence to suggest such equivalence was reported in the form of two measures of time judgement variability, Weber ratios and standard deviations across MOBS estimates. Variability was consistently lower in control conditions compared to saccadic ones, but did not differ across the critical experimental conditions in both Experiments 2a and 2b. In Experiment 2a, the variability trend differed from that found for subjective seconds, demonstrating that saccadic chronostasis is dissociated from a post-saccadic loss of timing sensitivity. Experiment 2c went on to suggest that other objects present in both pre- and post-saccadic displays can interfere with saccadic chronostasis when they undergo sudden displacement. It may therefore be the case that the saccade target object does not have particular significance in this respect.
Experiments 2a-2c were motivated by a specific interpretation of earlier saccadic chronostasis experiments: that saccade-related visual uncertainty is overcome by assuming that the post-saccadic percept holds good for the period of the saccade (and indeed slightly beyond, given the regularly observed additional constant). This theory was developed in the light of relevant data about object representations maintained in visual short-term memory and the nature of cross-saccadic knowledge. Object-oriented notions have become important in recent years for theories of space constancy, and an analogy was drawn between assumptions used to solve this problem (spatial stability of target objects) and the assumption hypothesised here to account for saccadic chronostasis (form constancy). It was suggested that the continuity of object representations might imply that methods known to break the former assumption (large shifts of location) might also break the latter. Experiment 2a broadly confirmed this intuition, but the implications of the three experiments reported here for the overall "working hypothesis" are not straightforward and deserve further discussion.

The suggestion regarding the backdating of the visual scene following a saccade is very general. While it has been deliberately phrased in terms of the visual scene as a whole, evidence thus far comes only from duration judgements made about the state of a single object initially in the periphery and subsequently precisely fixated. There has therefore been an implicit assumption guiding this research regarding the importance of this particular visual item, for which accurate information was lacking and, following a saccade, becomes available. In this sense it might be expected that the representation of the to-be-fixated object should be critical, an expectation that was apparently confirmed in Experiment 2a. Displace the object and the brain's assumption of continuity is broken. However, Experiment 2c provides important hints that this "object specific" notion of chronostasis may not be correct. Evidence suggests that a number of objects representations are maintained across a saccade (Deubel, Bridgeman, and Schneider, 1998; Irwin and Andrews, 1995). Knowledge about the temporal
continuity of one need not impinge upon representations of the others, yet Experiment 2c suggests that it does in the case of saccadic chronostasis.

This line of thought highlights an important area for future research on saccadic chronostasis: which aspects of the visual scene are affected? If assumptions underlying the illusion are influenced by representations of other objects, implying generalisation across the visual scene, what other representations are usually affected (predated)? At what level is object knowledge shared? Unfortunately, these types of considerations also necessitate consideration of what, exactly, constitutes a visual object. The term's use in the literature is often woolly (Driver et al, 2001), a trend that has sadly been repeated here. While certain formulations do attempt to specify the degree of detail inherent within a visual object or place these constructs within a hierarchical framework of higher- and lower-order representations, such attempts tend to be rather vague (e.g. the trade off between resolution and perceptual extent suggested for object files; Kahneman, Treisman, and Gibbs, 1992). It is clear that without a precise definition to drive theory a result like that of Experiment 2c is ambiguous; the letter displayed above the target counter might have formed a single perceptual object in concert with the counter, particularly given their initial presentation in the far periphery. Hence a single higher-order object might have had its continuous representation undermined by the letter shift.

Further research is needed to make inroads into these alternatives and address the questions these experiments have thrown up. In particular it might be fruitful to combine methodologies used to assess the maintenance of representations across saccades with the paradigm employed here. For example, a cluttered scene allows the formation of only a few object representations and can be used to assess both how many objects get maintained and what constitutes an object in a given context. It might be predicted that objects that are represented in these conditions can both support and disrupt saccadic chronostasis, whereas other identical objects that cannot be encoded due to capacity limitations would fail to do so. The results reported here also relate to other potentially relevant features of
object representations, such as the time course and visual range of their formation. In Experiments 2a and 2b the counter did not appear on screen until subjects had fixated and pressed the mouse key. Hence they can only have had knowledge of this object from fairly extreme peripheral vision, and typically only quite briefly (subjects soon get impatient to finish and start saccading immediately after initiating a trial). This is in contrast to Experiment 2c and those reported in Chapter 2. Nonetheless, saccadic chronostasis occurred, as did its modulation by target shifts. Within the context of the current object-dependent explanation, it appears that object representations are formed rapidly even in the periphery, as might be expected if they play a key role in processes like the cross-saccadic updating of visual space.

It should be noted that while the working hypothesis presented here suggests that visual information available after a saccade is backdated to fill in a period of perceptual uncertainty, it is possible to consider saccadic chronostasis as a predictive mechanism rather than one operating to alter conscious experience after a saccade. It is conceivable that the brain establishes an expectation about the state of a target object before a saccade is made, and that the resultant percept is only modified if this expectation is found wanting. Such an account seems to fit quite naturally with the finding that breaking an assumption about spatial continuity disrupts chronostasis. The backdating hypothesis is presented here because it seems more applicable to non-experimental situations like that in which the stopped clock illusion is typically experienced. It seems unlikely that an accurate prediction about the precise form of an object can typically be made, given that we usually make a great many saccades within a rapidly changing visual environment and have rather poor peripheral acuity. Nonetheless, the experimental procedures used here cannot clearly distinguish between these accounts because subjects repeatedly saccade to an identical target, making prediction relatively easy. The issue is an empirical one, but in the absence of relevant data the backdating account will be presented in preference, with the proviso that a predictive account will often fit the data equally well.
Regarding the analogy that has been drawn with theories of space constancy, there is no direct evidence here that the processes are actually related. However, it is interesting to consider physiological evidence relating to space constancy in the light of potential shared mechanisms. Cells in the lateral intraparietal area of monkeys show retinotopic mapping. Many of these cells appear to shift their receptive fields in the direction of upcoming saccades; when a stimulus is presented at the position a cell’s receptive field will occupy following re-fixation the cell begins to fire some 80 ms before the saccade is actually initiated (Duhamel, Colby, and Goldberg, 1992). This 80 ms value is interesting, being similar to the constant values obtained in the saccadic chronostasis experiments reported here (the size of the illusion over and above the duration of the eye movement). Could this be the event to which the post-saccadic precept is being predated? Receptive field shifts do not occur for attention shifts in the absence of saccades, in keeping with the results of Experiment 1d where the conscious manipulation of attention allocation did not influence saccadic chronostasis. In humans, posterior parietal cortex has been implicated as a critical region used to update visual space across saccades, with disruption of this region in a temporal window beginning around 100 ms before a saccade preventing the integration of extra-retinal information from earlier eye movements (Donkelaar and Muri, 2002). These authors employed a double step task, in which two lights were briefly flashed one after another, with saccades made to the remembered location of each in turn in complete darkness. They found that errors in first saccade extent, usually compensated for by extra-retinal mechanisms, propagated to the second saccade when trans-cranial magnetic stimulation was applied just before second saccade initiation. The overlap between processes of spatial updating and saccadic chronostasis is intriguing, in terms of both their shared pre-saccadic timing and the target shifts that undermine them, but any assertion regarding a common mechanism remains highly speculative.

A final point of discussion relates to the trend towards low control estimates in constant fixation conditions for these experiments. It has been
noted that these experiments differed from those presented in Chapter 2 in that white stimuli on a black background were used. Rose and Summers (1995) found overestimation of the time of the first of a train of visual targets using square light patches on a darker background. They manipulated square luminance (very bright verses very dim) and found no influence for this variable, but they did not go so far as to reverse the figure-ground luminance relationship. It is possible, then, that this change was important in the current experiments. However, the size of these authors’ effect was much greater and more reliable that that obtained here, and it is far from clear that there is any relation between them. Time order errors are another possible candidate (Hellstroem, 1985). However, the consistency of the trend found here compared to its absence in earlier experiments suggests that random fluctuation in stimulus magnitude and presentation order across trials are unlikely explanations, leaving a question as to why such a time order error should have emerged.

Regardless of the theoretical explanation, it has been demonstrated here that displacement of salient objects present in both the pre- and post-saccadic visual scene disrupts saccadic chronostasis. The appearance of objects does not. The possible effect of having salient objects disappear has not been tested, so it cannot be asserted that an object’s presence in both images is absolutely necessary for disruption. The displacements employed here imply target movement, although they are not phenomenally experienced as such (as in classic demonstrations of apparent motion). Does chronostasis occur for moving stimuli? Motion, of course, is simply a change in position over time. As such, an illusion of time might impact on our perception of position. This issue is one of those addressed in Chapter 4.
Chapter 4. Saccadic chronostasis and moving stimuli

In Chapter 3 the implications for saccadic chronostasis of shifting target and non-target objects were explored. It was demonstrated that a mid-saccadic shift of the saccade target, or of a character presented close to the saccade target, could disrupt the illusion. Such mid-saccadic shifts are not experienced as target motion, but do suggest the possibility that more typical cases of stimulus motion might interfere with the heuristic assumptions hypothesised to underlie saccadic chronostasis (i.e. object constancy across the saccade). Alternatively, prior knowledge about stimulus motion might elicit expectations about continued motion such that an assumption of object constancy would be easily maintained. Recent research has demonstrated that deviations from expected trajectories across saccades are relatively well detected (Gysen, De Graef, and Verfaillie, 2002). Specifically, when an 8° saccade is made to an object translating slowly (2.68° per second) across a screen, discrimination of small displacements (0.5-1.5°) is improved relative to saccades made to an identical stationary object. This advantage occurs for moving objects presented alone, and when their motion can be encoded relative to a stationary object (Gysen, Verfaillie, and De Graef, 2002a). This kind of data suggests that velocity information is coded for moving objects such that post-saccadic position can be predicted quite well. It seems logical that representations could be maintained for moving objects; indeed, the problem of representing objects that move over time provided a major motivation for proposing object-based representations in the first place (Kahneman, Treisman, and Gibbs, 1992). In this case, the hypothesis that saccadic chronostasis is related to the maintenance of object representations implies that the illusion will arise for moving objects as well as stationary ones.

If chronostasis does emerge for moving objects, a number of interesting questions arise. For a moving stimulus, changes in perceived time may produce changes in perceived position. If an observer saccades to
a moving stimulus and believes they have seen that stimulus for longer than is actually the case, do they therefore project its position backwards as well, believing that they initially saw it further back along its trajectory? In this case, a percept of motion would have to be retrospectively constructed such that it seemed to have occurred during the period of the saccade. Such an account would predict a systematic tendency to report stimuli as having been behind their actual positions at the point at which they were fixated. Alternatively, it might be that position is perceived veridically following a saccade, but the stimulus is still believed to have been perceived at an earlier time than is actually the case. In this case, no systematic errors would arise in reports of the first position of a post-saccadic stimulus, but the transition from pre- to post-saccadic position would appear to take no time. As a Brazilian journalist was kind enough to point out, such a phenomenon would have

Figure 4.1. Schematic of accounts integrating the perception of a constant velocity stimulus with the effects of saccadic chronostasis. The movement backfill account and two versions of the correct localisation account (with/without interpolation) are shown. The dotted region of the position traces represents perception that must be retrospectively “filled in” by the brain.
important real-life ramifications, most crucially as an explanation of linesmen's tendencies to incorrectly call strikers offside at football matches. These two accounts are presented schematically in Figure 4.1.

Prior to gathering data, the first of these accounts (the movement backfill account) seems more likely because of logical problems with the latter correct localisation account. If we were to perceive position correctly following an eye movement but ascribe the time of such a perception to be similar to or even precede the moment our eyes began to move, a stimulus moving with constant velocity during a saccade would appear to have jumped forward. This is not our everyday experience. It is possible to argue that position is not precisely maintained across saccades, with shifts often going unnoticed because the perceptual system assumes the continuity of key reference objects (Currie, McConkie, Carlson-Radvansky, and Irwin, 2000). However, the previously mentioned work comparing shift detection for moving and static stimuli suggests that humans are quite sensitive to trajectory shifts for moving objects (Gysen, De Graef, and Verfaillie, 2002) and that mechanisms of assumed continuity do not operate in the same manner for such stimuli (Gysen, Verfaillie, and De Graef, 2002b). The problem is that given the low movement speeds employed by these researchers, the size of the shifts employed (and found to be discriminable) were larger than that implied by a saccade-dependent discontinuity of the sort predicted here. Hence these data cannot really rule out the possibility that the shift simply goes unnoticed.

Another problem with the correct localisation account is that if stimulus position is correctly perceived, yet the stimulus is still judged to have been seen for longer than is actually the case, it ought to appear to accelerate. For any given period of time following the saccade (in which the stimulus moves a constant distance) velocity will appear slower than in the subsequent identical period of time, because the former period will be stretched out by saccadic chronostasis. This is an extension of the discontinuity problem noted above. If the stimulus leaps forward, then in maintaining constant velocity it must halt for a moment before resuming its
original speed (although the visual system might interpolate to produce a percept of smooth acceleration; see Figure 4.1). Again, introspection tells us this is not what we perceive. Nonetheless, caution is required, as the assumption that our perception of velocity is veridical has been challenged experimentally. Runeson (1974) had subjects judge the velocity profiles of a moving light dot, with distance from a stationary start point controlled as one of a variety of functions of elapsed time. These functions included constant velocity, various types of acceleration and deceleration, and functions modelling constant force applied against resistance. Subjects judged which of two motion patterns looked more constant, or attempted to graph the velocity profile of individual motion patterns. They showed a marked tendency to perceive motion patterns exhibiting rapid acceleration decreasing smoothly to constant velocity as being of constant velocity, while actual constant velocity appeared to be too fast initially and decelerate to a later constant speed. Real world objects rarely accelerate from standing in a step function, so it appears that perception may reflect intuitive physics.

In the context of the current discussion, a smooth decreasing acceleration function can be predicted by the correct localisation account if we assume interpolation; it might therefore appear as constant velocity. This suggestion is highly speculative, however. Runeson’s subjects had already fixated their target before it began moving, although they were free to subsequently track the moving object, so this data might not be relevant here. Perhaps more importantly, there are clear difficulties in assessing people’s perceptions regarding acceleration and velocity given that typical understanding of these terms may differ from the strict definitions provided in physics.

Although saccading to a stimulus implies that it has already been seen, the post-saccadic image is in a sense a fresh viewpoint containing new visual information. The situation is therefore further complicated because a number of other mislocalisation illusions are known to occur when a stimulus first appears in view. For example, briefly presented peripheral stimuli tend to be judged to be closer to the fovea than is actually the case (Muesseler, Van Der Heijden, Mahmud, Deubel, and Ertsey, 1999). Perhaps
of greater concern, motion can be an important factor. The most well known illusion with potential relevance here is the Fröhlich effect (Fröhlich, 1923). The first position of a fast-moving stimulus appearing suddenly (e.g. from the edge of a window) tends to be mislocalised in the direction of motion. The effect has been found using analogue and digital displays with both rotary and linear motion (Kerzel and Müsseler, 2002; Kirschfeld and Kammer, 1999; Müsseler and Aschersleben, 1998). Sometimes, however, the first position of such a stimulus is mislocalised in a direction opposite to motion (the onset repulsion effect; Hubbard and Motes, 2002; Thornton, 2002). Determining the conditions under which one or other illusion is likely to occur has proved complex, but key factors include stimulus velocity (the onset repulsion effect is observed at lower speeds) and the nature of the task used to assess initial position (Kerzel, 2002). Any displacements observed in the context of eye movements therefore need to be assessed in the light of such effects.

**Experiment 3a**

Before going on to test the two accounts of saccadic chronostasis in the context of moving stimuli described above, it is necessary to determine whether saccadic chronostasis occurs at all under these conditions. To this end, Experiment 3a employed a variant of the standard chronostasis paradigm (established in Chapters 2 and 3). Would the first digit of a counter be judged longer than subsequent digits when the counter itself moves with constant velocity before and after the saccade? One complication here is that given the length of time necessary for counter presentation (long enough to precede an eye movement and allow a comparison of intervals following it) and the size constraints of a CRT screen, linear motion in a single direction was impractical for all but very slow velocities. Linear motion that rebounds between two points or circular motion is the obvious alternative, but unfortunately any such regular motion contains temporal cues that might easily influence participants when making
a judgement about elapsed time. For this reason, the counter wandered in an unpredictable manner equivalent to making direction vary from frame to frame according to a random walk stochastic process (Chatfield, 1996). It was considered that if saccadic chronostasis occurred under these conditions it would probably also occur for more predictable types of movement.

Methods.

Participants. 12 subjects completed Experiment 3a (8 male, mean age 28.4, SD 5.6).

Apparatus. Subjects sat before a 22” CRT colour monitor refreshing at 60 Hz. Eye to screen distance was maintained at 41 cm using an adjustable chin rest. Horizontal eye movements were recorded from the left eye using an infra-red eye tracker (Microguide 1000 spectacles, low-pass filtered at 40 Hz) and sampled at 200 Hz. Stimuli were black on a white background, subtending approximately 0.5°. They consisted of a cross and/or a digital counter, initially set to “0” and counting through the digits “1” to “4”. In conditions where the digital counter moved, it began with a direction setting randomly generated in the range 0 to 360° with steps of 3.6°. On each subsequent frame, this heading was altered by adding one of six randomly generated values: -10.8°, -7.2°, -3.6°, 3.6°, 7.2°, 10.8°. The counter was moved in the resulting direction by 1 or 2 pixels, as long as doing so would maintain its position within a 10° by 10° square region centred upon the counter’s initial position. When this condition was not fulfilled, an alternative heading alteration value was generated with a larger range of possible values, such that substantial changes in direction could occur at region edges to maintain the counter within the designated area. Note that while in theory such motion has constant velocity, in practice the pixelated nature of the presentation medium meant that this was not the case. For any given direction of motion, horizontal and vertical components had to be derived. For example, with a desired shift of 1 pixel, the actual shift will be

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substantially biased by rounding error because both horizontal and vertical components can only take values of \(-1\) or \(1\), yielding actual displacements of either 1 or \(\sqrt{2}\) pixels. For this reason, instantaneous velocity fluctuated slightly. With a desired shift of 1 pixel per frame (2.86° per second) it averaged 3.25° per second. For a desired shift of 2 pixels per frame (5.71° per second) it averaged 5.97° per second. The experiments were controlled by a PC interfaced with a 12 bit A/D card (National Instruments DAQ 1200).

**Design.** A 2 x 3 factorial repeated-measures design was employed. The first factor *eye status* compared a voluntary saccade (average 20°) to a constant fixation control at equivalent eccentricity (±10°). The second factor *movement speed* had three levels: stationary (0° per second), slow movement (3.25° per second) and fast movement (5.97° per second). Each of the six resultant conditions was tested in a separate type of block, with four such blocks completed per condition. Order was counterbalanced across subjects and alternated. The second factor was counterbalanced over the first six subjects, while the first factor was counterbalanced between the first and second sets of six subjects. Hence, the first subject received the order: stationary fixation, slow fixation, fast fixation, stationary saccade, slow saccade, fast saccade, repeated four times. The second subject received four repetitions of the order: slow fixation, fast fixation, stationary fixation, slow saccade, fast saccade, stationary saccade, and so forth.

**Procedure.** In saccade blocks, subjects fixated a cross on one side of the screen while a target “0” was displayed on the other side. The trial was initiated with a mouse key press. In the slow and fast movement conditions, the “0” began to move at this point, with the counter remaining in motion throughout subsequent changes of digit. Subjects made a voluntary saccade towards the “0”, with eye movement triggering a change of digit to a “1” when the saccade had travelled one fifth of the distance to target. The “1” remained on screen for 400-1600 ms; subsequent digits (“2”, “3”) remained
on the screen for 1 second 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. Saccade start/end points were calculated automatically using a velocity criterion; difference values between sample n and sample n-3 were compared to thresholds based on background signal noise. Trials where the first saccade recorded did not exceed 50% of the total distance recorded (summed across all detected saccades) were excluded on line and repeated immediately. This value was lower than for experiments reported in Chapter 2 because subjects tracked the counter after their saccade, and this movement was occasionally interpreted as further saccades by the computer. In control (constant fixation) blocks, subjects simply fixated a "0" at equivalent eccentricity that changed to become the judged digit ("1") 500 ms after the subject's mouse key press. For slow and fast movement conditions, the "0" began to move immediately after the mouse key was pressed. Direction of saccade (saccade conditions: left to right and vice versa) or position of the counter (control conditions: left or right) alternated every trial.

In all conditions, the duration of the "1" was controlled by a MOBS procedure (low boundary 400 ms, high boundary 1600 ms, initial presentation random 800-1200 ms, five reversals to terminate). Blocks were of variable length, typically 6-20 trials. Subjective second estimates were derived as the mean of the four MOBS termination values in each condition. In the saccade conditions, each estimate was corrected post hoc to match the time the "1" was on screen following target foveation by subtracting the average time the eye was in motion following the triggered change of digit (averaged across all four blocks in each saccadic condition). The experiment took around ninety minutes to complete.

Statistical analyses. Standard parametric tests were used to assess differences across conditions with alpha set at 0.05 and appropriate corrections made for sphericity violations (as per Experiment 1d).
Results and discussion.

Saccade characteristics. In the stationary condition, first saccades took an average of 69 ms (range 52-84 ms) and covered an average 19.4° of visual angle. With slow movement, these values were 66 ms and 19.4°, while fast motion yielded average saccades taking 68 ms and covering 19.6°. In the two movement conditions, these mean values reflected individual saccades of quite variable extent (the counter began to move before the saccade was initiated). Mean standard deviation across all saccades was 2.61°, 3.45° and 4.32° for stationary, slow movement and fast movement conditions respectively. Corrective saccades were common.

![Graph showing time estimates](image)

Figure 4.2. Mean time (ms) matched to one second for three conditions involving saccades of 20° to a counter that remained stationary or moved at 3.25°/sec or 5.97°/sec. Also shown are three control conditions (constant fixation) at matched speeds. Error bars show standard deviations.

Time estimates. Figure 4.2 shows the mean corrected time estimates across subjects in all six conditions. Control estimates were quite accurate, being very slightly above 1000 ms for all movement conditions. Values in the saccade conditions are noteworthy for a number of reasons. Firstly, in contrast to all previous experiments, there is only a very small decrease in the value judged equal to one second following a saccade compared to the relevant control when the counter remains stationary.
Secondly, a more typical result is obtained when the counter moves slowly, with a reduced subjective second. Finally, this effect appears to be reduced for faster movement of the counter. Statistical analysis was only partially revealing. A 2 x 3 ANOVA showed no significant effects. However, three planned comparisons were still conducted between saccade and control conditions at each level of movement speed, revealing a significant difference between control and saccade conditions only for slow counter movement ($t = 2.891, df = 11, p = 0.015$).

These results are difficult to translate into strong assertions. Power was 0.85 to detect a predicted 110 ms difference between control and saccade conditions for the stationary counter (planned comparison, $\alpha = 0.05$). The failure to replicate previous findings may reasonably be interpreted as a type II error, given a $\beta$ value of 0.15 and the number of experiments reported thus far. Given that conditions were essentially identical to those in which saccadic chronostasis has repeatedly been found, few alternative explanations are available. It is possible that the context in which this condition was experienced in the current experiment (alongside conditions with a moving counter) exerted some influence on subjects’ judgements, but this explanation is rather strained. Regarding the difference between the slow and fast movement conditions (saccadic chronostasis only obtained in the slow condition) conclusions must again remain tentative. The trend suggests that chronostasis might be reduced for higher velocity stimuli, but power was only 0.44 for the control/saccade comparison at this level of movement speed and in the absence of a significant ANOVA the question must remain open. The only cautious conclusion that seems justified by these data is that saccadic chronostasis can be obtained for at least the lower movement speed tested here. With this in mind, we may reasonably progress to test the competing accounts of the resultant motion perception presented in the introduction.

Experiment 3b
The movement backfill account suggests that when the eyes saccade to a moving target and it is perceived to have been seen for a period beginning before movement initiation (saccadic chronostasis) a perception of its prior motion will be created to fill the saccadic gap. The first position seen following the saccade will therefore be judged to be further back along the path of motion than is in fact the case. In addition, this error will grow with saccade extent. Experiment 3b tested this prediction. Because initially perceived motion is known to influence the localisation of stimulus onset (Fröhlich, 1923; Thornton, 2002) and it is not clear to what extent motion after a saccade should be considered "initially perceived," two control conditions were employed. In the first, a comparable moving stimulus appeared at fixation, while in the second this stimulus was stationary but presented only briefly.

Methods.

Participants. 10 subjects completed Experiment 3b (8 male, mean age 32.0, SD 7.6). 2 had previously participated in experiment 3a.

Apparatus. Subjects sat before a 14” CRT colour monitor refreshing at 60 Hz. Eye to screen distance was maintained at 30 cm using an adjustable chin rest. Horizontal eye movements were recorded from the left eye using an infra-red eye tracker (Microguide 1000 spectacles, low-pass filtered at 40 Hz) and sampled at 200 Hz. Stimuli were black on a white background. They consisted of a cross, subtending approximately 0.5°, and/or a clock face. The clock face had a radius of 1.8° and was constructed from a circle with 12 equally spaced dividers extending inwards 0.26° from its circumference in the positions hour markers occupy on a typical clock. When active, it had a single hand, extending from its centre to its circumference and rendered in a slightly thicker line. When in motion, the hand moved in a clockwise direction with an angular velocity of 1
revolution per second.¹ This yielded differing tangential velocities along its length, growing from 0° per second at the centre to 11.3° per second at the circumference. The experiments were controlled by a PC interfaced with a 12 bit A/D card (National Instruments DAQ 1200).

**Design.** A 3 x 2 factorial repeated-measures design was employed. The first factor *stimulus condition* had three levels: flashed (clock hand briefly presented at fixation), moving (clock hand appearing at fixation with constant velocity) and post-saccadic (clock hand appearing mid-saccade with constant velocity). The second factor *saccade size* compared a 10° saccade with a 40° saccade in the post-saccadic condition, or clocks presented at equivalent eccentricities (±5°, ±20°) at the other two levels of stimulus condition. Each of the six resultant conditions was tested in a separate type of block, with a single block completed per condition. Each block contained 20 trials. Order was partially counterbalanced across subjects. As in Experiment 3a the three-way factor was counterbalanced over the first six subjects, while the two-way factor was counterbalanced between the first and second sets of six subjects, although the final two subjects necessary to complete this process were not tested.

**Procedure.** In post-saccadic conditions, subjects fixated a cross on one side of the screen while the clock face (without hand) was displayed on the other side. The trial was initiated with a mouse key press. Subjects made a voluntary saccade towards the clock, with eye movement triggering the appearance of the rotating hand when the saccade had travelled one fifth of the distance to target. The hand appeared at a random position on the clock and continued to rotate for a random time interval in the region 500-1500 ms. Saccade start/end points were calculated and trials rejected as per Experiment 3a, except that the first saccade distance criterion was raised to 90% of the total distance recorded for all saccades. The clock hand remained in its final position for 500 ms before it was replaced with a

¹ Angular velocity is here referred to in revolutions per second to avoid confusion with
window displaying a replica of the clock with the hand pointing to twelve o’clock. Subjects used the mouse and an adjacent scroll bar to move the position of the hand until it matched the position at which they felt they had first seen it, then terminated the trial by depressing an on-screen button.

For moving conditions, only the empty clock was initially displayed. Subjects fixated it, then initiated the trial with a key press. The clock hand appeared 500 ms later at a random position, and the trial proceeded as for post-saccadic conditions. In flashed conditions, the procedure was the same except that the clock hand simply appeared at a random location 500 ms after trial initiation, remained on screen in the same position for 100 ms, then disappeared, with the response window appearing 500 ms later. Direction of saccade (post-saccadic conditions: left to right and vice versa) or position of the clock (flashed and moving conditions: left or right) alternated every trial. The experiment took around thirty minutes to complete.

Statistical analyses. The dependent variable was the mean average error in each condition. In the flashed and moving conditions, error was calculated for each trial as the difference between the position the hand had first appeared in and the position to which the subjects subsequently set the replica clock, in units of milliseconds (1 ms = 1/1000th of a revolution). Positive errors indicated that the subject had judged the hand to appear ahead of its actual starting position and vice versa. For the post-saccadic conditions, the same procedure was used except that the position the hand first appeared in was adjusted to reflect the position it had occupied when the subject’s eyes first fixated it. This was accomplished by adding the time the eyes had been in motion since the hand’s appearance had been triggered, on a trial by trial basis. In addition to standard parametric tests, non-parametric ANOVAs (Friedman’s rank test) were used to assess differences across conditions.
Results and discussion.

Saccade characteristics. In the 10° condition, first saccades took an average of 49 ms (range 36-57 ms). For 40° saccades, this value was 108 ms (range 88-135 ms), a difference of 59 ms. Corrective saccades were common.

![Figure 4.3](image_url)

**Figure 4.3.** Mean error (ms) relative to actual onset position for three conditions involving judgements about the initial position of a clock hand that was flashed at fixation, moved with constant velocity after appearing at fixation, or moved with constant velocity after appearing at saccade target mid-saccade. Each condition is shown at two levels of saccade size/eccentricity. Error bars show standard deviations.

Accuracy of initial position localisation. Figure 4.3 shows the mean error across subjects for all six conditions. In all conditions subjects judged the clock hand to have appeared slightly back from its actual onset position. This error tendency appears greater in the moving and post-saccadic conditions. Because standard deviations vary greatly across levels of stimulus condition, parametric tests were not deemed appropriate for this comparison (therefore ruling out a two-way ANOVA). Two Friedman tests were conducted, one at each level of saccade size, to assess changes across stimulus condition, but failed to reach significance in either case, albeit only narrowly for the 40° conditions (chi-square = 5.6, df = 2, p = 0.061). Six one-sample t-tests were used to assess deviations from zero for each condition; Bonferroni corrections meant that only the 10° flashed condition was significant (p = 0.042) although the 40° flashed and 40° post-saccadic...
conditions approached significance (p = 0.054 and p = 0.09 respectively). The hypothesised difference between post-saccadic conditions for 10° and 40° saccades was assessed as a planned comparison and was significant (t = 2.575, df = 9, p = 0.03). No such significant difference emerged for the flashed and moving conditions.

In evaluating the experimental hypothesis, the critical assessment must be based not only upon statistical significance but also on the magnitude of the effects obtained. Although there is some statistical support for differential perceived backwards displacements with varied saccade extents, the overall errors (16 and 31 ms for the 10° and 40° conditions respectively) are far smaller than the movement backfill account would predict. Given average saccade durations of 49 and 108 ms, a localisation error of similar magnitude would be expected, and the experiment had good power to detect effects of this size (one-sample t-tests: power = 0.99 at α = 0.008). The size of the effect is particularly important because a small negative shift would be predicted if subjects had some awareness of the clock hand towards the end of their saccade (although the significant difference between saccades of different sizes speaks against this interpretation). Overall, therefore, the movement backfill account is not supported by this data, except perhaps in a modified more limited form.

Regarding the non-saccadic conditions, the flashed conditions showed a small negative bias that was reliable at ±5° eccentricity. The cause of such a bias is not clear, but its size (about 3 minutes of visual angle at the circumference of the clock) suggests that it is of limited importance for everyday perception. The moving conditions showed a non-significant trend in the direction of the previously reported onset repulsion effect. With linear motion and a pointing task (the current experiment used a constrained pointing task) onset repulsion is found with slow velocities similar to the tangential velocity of the clock hand used here (Kerzel, 2002; Thornton, 2002). Its magnitude is typically in the range 20 to 60 min arc, equivalent to 29 to 88 ms at the circumference under current task conditions. Power was 0.99 to detect a one sample change of 29 ms at α = 0.01, suggesting that the
failure to find one here is statistically legitimate. If viewed in terms of angular velocity, rotating lines have previously been found to elicit powerful Fröhlich effects at rates of 0.5-1.5 revolutions per second (effect size 0.03 to 0.17 revolutions displacement, equivalent to 30 to 170 ms here; Kerzel and Muesseler, 2002; Kirschfeld and Kammer, 1999). However, these studies have used line stimuli of considerable length, giving a much higher tangential velocity at the circumference than that employed here. Perhaps more importantly, only line stimuli projecting across the entire diameter of the circle produced effects in the latter study; a massively reduced effect was found for a “half line” equivalent to the clock hand used here. The failure to find either a Fröhlich or onset repulsion illusion in the present study is therefore broadly consistent with a rather complex previous literature.

Experiment 3c

Experiment 3b failed to find evidence supporting the movement backfill account, at least in its fullest form. Experiment 3c was designed to search for evidence in favour of the alternative correct localisation account. To recap, the correct localisation account suggests that following an eye movement to a stimulus moving with constant velocity, the first position of the stimulus will be perceived correctly, but the observer will believe that they have seen the stimulus in this position for longer than is actually the case. Two versions of the correct localisation account have been suggested, one in which the stimulus is perceived to accelerate suddenly from rest at this point and one in which this acceleration is perceptually smoothed by a process of interpolation. Both accounts predict that a continuously moving stimulus will be perceived to have jumped forward slightly during a saccade, although this jump may be masked by the visual system’s failure to precisely code stimulus position. This in turn implies that the stimulus will be judged maximally continuous when it in fact stops for the duration of the
saccade, occupying the same spatial location both prior to and following eye movement. Experiment 3c tested this prediction.

Methods.

Participants. 20 subjects completed Experiment 3c (14 male, mean age 29.2, SD 6.7). 3 had previously participated in experiment 3a.

Apparatus. Subjects sat before a 14” CRT colour monitor refreshing at 60 Hz. Eye to screen distance, which varied between conditions (22 or 58 cm) was maintained using an adjustable chin rest. Horizontal eye movements were recorded using AC electro-oculography (D150 amp: Digitimer; band pass filtered 0.032-30 Hz) and sampled at 200 Hz. Electrodes were placed on the outer canthus of each eye. Stimuli were black on a white background. They consisted of a cross, subtending approximately 0.5°, and/or a clock face. The clock face had a radius of 1.8° and was constructed from a circle with 12 equally spaced dividers extending inwards 0.26° from its circumference in the positions hour markers occupy on a typical clock. When active, it had a single hand, extending from its centre to its circumference. When in motion, the hand moved in a clockwise direction with an angular velocity of 0.390625 revolutions per second (one revolution every 2560 ms). This yielded differing tangential velocities along its length, growing from 0° per second at the centre to 4.4° per second at the circumference. The experiments were controlled by a PC interfaced with a 12 bit A/D card (National Instruments DAQ 1200).

Design. A 2 x 2 factorial repeated-measures design was employed. The first factor eye status compared a saccade to the clock to a constant fixation control. The second factor saccade size compared a 22° saccade with a 55° saccade in the saccade condition, or clocks presented at equivalent eccentricities (±11°, ±27.5°) in the control condition. Each of the four
resultant conditions was tested in a separate type of block, with four blocks completed per condition. Order was counterbalanced across subjects and alternated in a manner similar to Experiment 3a. The first factor was counterbalanced over each pair of subjects, while the second factor was counterbalanced between the first and second sets of ten subjects, with one block from each condition completed in turn.

Procedure. In saccade blocks, subjects fixated a clock on one side of the screen with its hand pointing to a random position. They initiated the trial with a mouse key press, at which point the clock hand began to rotate. They then made a voluntary saccade away from the clock towards a cross on the other side of the screen. Eye movement triggered the disappearance of both the cross and the original clock and the appearance of a second clock at the saccade target location. This change occurred when the saccade had travelled one fifth of the distance to target. The second clock hand’s initial position was shifted by a variable amount relative to the final position of the first clock at this point (see below). It then continued to rotate for a random time interval in the region 980-1580 ms. Saccade start/end points were calculated and trials rejected as per Experiment 3b. The clock hand remained in its final position for 500 ms before a response window appeared allowing subjects to indicate whether they thought the clock had jumped forwards or backwards during their saccade (forced choice). They were told to make this judgement relative to the position they would expect to see the clock in if it had continued moving with a constant speed, i.e. to take account of their saccade time.

For the constant fixation blocks, only one clock was displayed. Subjects fixated it, then initiated the trial with a key press. The clock began to move from its initial random position 200 ms later. Subjects were required to make a non-speeded mouse key press shortly after this point, which caused the clock to briefly blank then reappear (appropriately shifted forwards given the elapsed time) having had its hand shifted forwards or

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2 This unusual value was selected to conform with studies performed by Patrick Haggard
backwards by an additional variable amount. The blank period was intended to mimic the period of a saccade, and was set to 70 ms at ±11° eccentricity and 140 ms at ±27.5° eccentricity (± screen refresh variability). The trial then continued as for saccadic conditions. Direction of saccade (saccade conditions: left to right and vice versa) or position of the clock (constant fixation conditions: left or right) alternated every trial. In all conditions, the clock hand's variable shift forwards or backwards was controlled by a MOBS procedure (low boundary -600 ms, high boundary 600 ms, initial presentation random -200 to 200 ms, five reversals to terminate). Blocks were therefore of variable length, typically 6-20 trials. The experiment took around one hour to complete.

**Statistical analyses.** Estimates of the shift value at which subjects perceived continuous movement were derived as the mean of the four MOBS termination values in each condition. This value, hereafter referred to as the continuity point, was in units of milliseconds (1 ms = 1/2560^{th} of a revolution). Positive values indicated that the subject required the hand to appear ahead of its correct position to perceive continuous motion and vice versa.

**Results and discussion.**

**Saccade characteristics.** In the 22° condition, first saccades took an average of 69 ms (range 52-86 ms). For 55° saccades, this value was 128 ms (range 83-194 ms), a difference of 59 ms. Corrective saccades were common.

**Shift values at the point of subjective continuity.** Figure 4.4 shows mean continuity points across subjects in all four conditions. An initially striking feature of the data is its high variability. Regarding the pattern of means, the continuity point appears to be shifted forwards slightly for control}

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using a Libet clock paradigm.
conditions and backwards for saccade conditions. A 2 x 2 ANOVA confirmed this as a main effect of eye status (f = 7.251, df = 1,19, p = 0.014) but did not reveal a main effect for saccade size or an interaction. The correct localisation account predicts a negative effect for saccadic conditions, with an effect size equal to or perhaps even greater than the duration of the saccade. The data provides statistical support for the notion that saccade conditions produced negative continuity points relative to control conditions, but the size of this negativity does not appear to scale with the size of the saccade. The trend is in the opposite direction, although the planned comparison between saccades of 22° and 55° was not significant. However, noise in the data was a real issue here, with power to detect the predicted difference of 59 ms (difference in average time to complete 22° and 55° saccades) a pitiful 0.26 for α = 0.05. To obtain power of 0.8 for this comparison would have required a rather unmanageable n = 88. The present experiment therefore offers limited evidence for or against the correct localisation account.

Regarding why judgements in this task should have proved so inconsistent, it seems likely that subjects had difficulty dealing with the
instruction to judge whether the clock hand had jumped forward or backwards *relative to the position it would otherwise have reached*. In the control conditions, they were clearly able to take some account of the gap (otherwise negative values and a larger difference between the two levels of saccade size would have been observed) but strategic differences may have emerged between subjects, particularly for the saccade conditions. These considerations stress the potential role of cognitive confounds in the current experiment; thinking too hard about where the hand ought to be might override lower level perceptual mechanisms. The answer may lie with a future analysis employing criterion free measures (as in signal detection theory) to seek differential sensitivity values for shifts with and against motion at various shift values.

**General discussion**

The research presented in this Chapter addressed two questions. Firstly, does saccadic chronostasis occur for moving stimuli? Secondly, if so, what are the implications for the resulting perception of motion? Experiment 3a produced some evidence to suggest that saccadic chronostasis can be obtained for stimuli moving with near-constant velocity but erratic motion paths. At least for low movement speeds, such stimuli were judged to have been perceived for longer than was actually the case following a saccade. Experiment 3b attempted to find evidence supporting the movement backfill account, in which a perception of continuous stimulus motion across the saccadic gap is constructed retrospectively. This account predicts that the first position of a moving stimulus seen following a saccade will be systematically misperceived back along the stimulus' motion path by an amount dependent upon saccadic duration. The evidence did not favour this view; only a small backwards displacement was observed. An alternative account predicts that a moving stimulus' post-saccadic position is correctly perceived and retrospectively extended across the saccadic gap without motion or with interpolated acceleration.
Experiment 3c tested one prediction of this correct localisation account: that a stimulus would be perceived to have constant motion when it actually remained static across the duration of a saccade. Again, data did not support this account, with real motion plus a very small backwards displacement being perceived as continuous. The results of these experiments are therefore problematic for both accounts of the interaction between saccadic chronostasis and motion perception in conscious experience offered in the introduction. Three possible resolutions are offered below.

1. Differences in the stimuli employed yielded questionable results. In Experiment 3a, as in all previous saccadic chronostasis experiments, a digital counter was used as the stimulus. The counter moved continuously but in an erratic manner. In Experiments 3b and 3c a clock face with a moving hand was used, and the motion of the clock’s hand was entirely predictable. Movement speeds are difficult to equate between rotating and translating stimuli and no attempt was made to do so. The rotating stimuli used in Experiments 3b and 3c were not continuous, in the sense that the post-saccadic stimulus only appeared and began to move during a saccade rather than being initially in motion whilst in the periphery. These differences may have been important. In particular, the accounts tested in Experiments 3b and 3c assumed that saccadic chronostasis was occurring based on the results of Experiment 3a, but this assumption may have been incorrect. It was suggested that if saccadic chronostasis was found for erratic motion it would probably be found for more predictable motion, but this logic may be faulty. The experiments presented in Chapter 3 and their subsequent interpretation casts doubt on the likelihood of experiencing saccadic chronostasis when the stimulus is not present in both pre- and post-saccadic views. Unfortunately, Experiments 3b and 3c used exactly such a stimulus configuration. If saccadic chronostasis was not occurring in Experiments 3b and 3c, it is hardly surprising that the hypothesised perceptual effects were not obtained.
2. *Both accounts are partially correct.* In Experiment 3b, a small backwards shift in perceived initial position was observed. This shift was dependent upon saccade size, making incomplete suppression of the post-saccadic image prior to fixation less likely as an explanation. However, the size of the effect was small compared with the duration of the saccades that preceded it. In Experiment 3c, the post-saccadic position of the clock did have to be shifted backwards relative to continuous motion to be perceived as continuous, at least for short saccades. The result for longer saccades in Experiment 3c is difficult to interpret, but taken together the experiments might suggest a kind of hybrid account in which some motion backfilling occurs, giving rise to a smaller-than-predicted mislocalisation in Experiment 3b and a similarly smaller-than-predicted discontinuity for continuous motion in Experiment 3c. The hybrid account is still not well supported because the numbers don’t neatly add up (particularly for longer saccades) but noisy data, particularly in Experiment 3c, may have undermined it.

3. *Dissociations exist between visual experience and time perception.* It is of course possible that neither account presented so far is correct. Their sufficiency (in the sense of being exhaustive) rests on the premise that systems responsible for different aspects of perception must share information and agree, and that conscious experience reflects the real-time experience of this agreed and unified representation. The latter clause of this premise represents a kind of Descartes-inspired fallacy that, as reviewed in Chapter 1, rests on very questionable assumptions (the Cartesian theatre model; Dennett and Kinsbourne, 1992). The former assertion, that different systems share information and must agree, is similarly dubious. Functional specialisation lies at the heart of our current understanding of the brain, while the idea that some degree of information encapsulation exists for specific systems has had a considerable impact (Fodor, 1985). A number of well-known dissociations have emerged between separate systems. For example, it has been argued that conscious visual perception and the visual control of action depend on anatomically and functionally distinct brain
regions that can be independently affected by visual illusions (Goodale and Milner, 1992). The precise nature of such a dissociation remains highly controversial, but examples continue to proliferate in the literature (e.g. the recent demonstration that saccade-dependent compression of visual space does not influence pointing movements; Burr, Morrone, and Ross, 2001). It might be objected that the current experiments appear to show a dissociation between two perceptual components that are simultaneously available to consciousness (vision of a stimulus and the time for which it is perceived to have been seen) rather than a conscious component and a non-conscious component (as in vision-action dissociations). However, the visual system provides examples of conscious dissociations too. We can perceive motion without perceiving movement, as in the waterfall illusion, although there may be a rather complex interaction between the two perceptions (Nishida and Johnston, 1999). Besides, duration estimation necessarily reflects the integration of sensory experience over time, so is not in this sense “simultaneous” with perception and might easily be tampered with without leaving any telltale clues. Is it so unreasonable that we might be able to feel a stimulus had been perceived for a given period of time without having phenomenologically “seen” it for the entire duration?

Concluding remarks. These three explanations of the results of Experiments 3a to 3c could in part be teased apart with a better designed replication. Stimulus differences should be minimised across studies. For example, if the counter in Experiment 3a were replaced with one that required a shorter presentation duration (e.g. a circle that changed colour to mark discrete periods of 500 ms and eschewed the latter redundant comparison periods) saccadic chronostasis could be assessed for continuous linear motion. The same stimulus could then be used to assess perception of onset position (as per Experiment 3b) and sensitivity to forward or backwards displacement (as per Experiment 3c). Perhaps most interestingly, each effect could be observed in isolation (e.g. just a duration question) or in combination with the others (e.g. a duration question and an onset position question).
Multitasking complicates the protocol but allows an analysis of whether one perception comes to dominate others when specific questions are included, an issue that is relevant when considering perceptual dissociations. The resultant highly-factorial design would be demanding for individual subjects but potentially very revealing. No further studies involving stimulus motion are reported here, but the question of dissociations in the experience of saccadic chronostasis is once again taken up in the following chapter.
Chapter 5. Registration/dissociation between saccadic chronostasis and motor timing/tactile stimulation

In Chapter four, a number of possible explanations were proposed for the failure to obtain results favouring a single coherent experience integrating saccadic chronostasis with the perception of a moving stimulus. One of these explanations suggested that such a unitary experience is not logically necessary. Separate systems may operate upon the same sensory information in different ways and produce behaviour that is differentially affected by illusions. Even for stimuli that reach conscious awareness, incompatible input may be experienced without contradiction, or smoothed over to produce a single dominant perception (as in binocular fusion). In this chapter, two experiments are presented that search for evidence for the separability of the experience of saccadic chronostasis from alternative sensory and motor streams. The first experiment examines the illusion’s interaction with the motor system, while the second experiment assesses its implications for the conscious ordering of events arising in both affected and unaffected sensory modalities. The central question is whether experiencing chronostasis must necessarily impinge upon the entire cognitive architecture in a mutually consistent manner.

Experiment 4a

The idea that separate visual cortical areas exist to analyse different components of visual stimuli is well established (e.g. Zeki, 1978). It has been suggested that separate ventral and dorsal pathways exist for processing “what” and “where” information (Goodale and Milner, 1992; Mishkin, Ungerleider, and Macko, 1983). The ventral pathway appears specialised to provide a cognitive representation of objects in the visual scene. It is assumed to form the basis of visual consciousness, encoding stimuli in an object-centred (allocentric) manner. The dorsal pathway extracts visual information necessary for visuomotor behaviour. Its contents
are often hidden from consciousness, with stimuli encoded in viewer-centred (egocentric) co-ordinates. This classification was initially proposed based upon neurophysiological and neuropsychological work. However, it is also supported by demonstrations that certain visual illusions can affect conscious perception without influencing the accuracy of the motor system. For example, an "induced Roelofs effect" (in which an object is perceived as being displaced based on the position of the surrounding frame) has no influence on accuracy for rapid jabbing movements (Bridgeman and Huemer, 1998). Whether an illusion affects conscious perception and/or motor accuracy is expected to depend upon the neural level (pre or post ventral/dorsal pathway separation) at which it arises, with early-visual illusions affecting both pathways. In the simultaneous tilt illusion, a central region of stripes shows an illusory tilt based on the orientation of stripes in a surrounding grating, probably as a result of local contour interactions (lateral inhibition) in primary visual cortex. In the rod and frame illusion a rod appears tilted based on the orientation of a distant frame (a relative effect occurring over considerable visual distances). The former illusion affects motor behaviour, while the latter does not, reflecting their presumed sites of neural influence (Dyde and Milner, 2002).

A number of studies have questioned such interpretations on methodological grounds or because of non replications (see Carey, 2001, for a review). Others have attempted to flesh out the ways in which the two pathways might still interact beyond their apparent bifurcation. Some aspects of motor control require information that must be derived from memory-based object knowledge. Grip force, for example, is predictive, and depends upon features such as estimated friction and weight. Despite being a component of a motor act, it is influenced by the Ponzo visual illusion, which uses converging or diverging lines to influence the perception of object size. Grip aperture, by contrast, is unaffected by this illusion (Jackson and Shaw, 2000). Demonstrations like this qualify and add detail to the two pathway model while supporting it as a general framework (although see Smeets, Brenner, de Grave, and Cuijpers, 2002).
While the current experiment was loosely inspired by this literature, there are important differences to keep in mind when considering the way saccadic chronostasis might differentially affect visual judgements and motor performance. The dissociations described above are interpretable within the context of the two visual pathway model. Comparing time judgements with tapping behaviour (the approach taken here) does not map onto this scheme; saccadic chronostasis may rely upon ventral processing, but rhythmic tapping is not a classic dorsal visuomotor task. Both tasks necessarily share an important timing component, and there is evidence to suggest that sensory timing and motor timing may rely on similar neural structures, primarily the cerebellum, basal ganglia and fronto-parietal cortex (Hazeltine, Helmuth, and Ivry, 1997). Strong correlations emerge between performance in repetitive tapping and duration discrimination tasks, again suggesting a common mechanism (Keele, Pokorny, Corcos, and Ivry, 1985). We might therefore expect that an illusion that affected temporal judgement might also affect tapping, although this would depend upon the particular components of any internal clock system that are shared by both systems. As reviewed in Chapter 1, internal clock models of perceptual timing often posit components such as a pacemaker and a reference memory. Models of motor timing also require specific and often overlapping components (e.g. the timekeeper in the two-process model of continuation tapping; Wing and Kristofferson, 1973) but not all components will necessarily be engaged in all tasks. Assessing the degree to which the illusion is found for different types of task may give an insight into when and where it emerges within the cognitive and neural architecture.

In the current experiment, the standard saccadic chronostasis time judgement task is compared with an instruction to tap every 333 ms following eye movement so as to synchronise with the counter change on every third tap. The experiment has three stages: a baseline stage, in which saccadic chronostasis is assessed; a tap stage, in which tapping is attempted with the first counter interval set at the subject's previously derived subjective second value; and a reassessment stage, in which saccadic
chronostasis is re-evaluated in the presence of taps. The study is exploratory, without a clear a priori hypothesis, but two alternative outcomes are considered here and outlined in Figure 5.1. Firstly, it might be that saccadic chronostasis emerges at a neural level common to both judgement and production tasks (for example if it arose from an alteration in the functioning of an internal clock used to mark out time in both situations). In this case, subjects will initially display saccadic chronostasis, as indexed by the standard forced choice judgement task. In the second phase, in which they are required to tap after a saccade, the pattern of their first three taps will reflect the timecourse of the process that caused saccadic chronostasis. Their third tap, aimed to synchronise with the change of digit, will be approximately accurate, but the first two will be displaced backwards by a constant amount such that the first tap appears very early. This pattern indicates that the shift in time perception has occurred early enough to influence the decision to initiate the first tap (shown in Figure 5.1). If the shift occurs rather later or is spread out over the period of the subjective...

Figure 5.1. Schematic of experimental procedure incorporating strong predictions regarding the impact of saccadic chronostasis on a shared/dissociated perceptual and motor timing process.
second, the interval between the first and second or second and third taps might be short, or the first three taps might be equally spaced but objectively too rapid. In the third phase of the experiment, saccadic chronostasis will again be obtained alongside the tapping task.

Alternatively, saccadic chronostasis might not affect the timing processes underlying rhythmic tapping. In this case, the illusion will be obtained in the first phase, but when the tapping task is introduced in the second phase, subjects will initially come in late with their third tap (although they might be expected to rapidly learn to speed the first three taps and achieve synchrony). At this point the two systems (perceptual and motor) are in conflict. This discrepancy might be consciously experienced and cause subjects to recognise that the first interval is too short. Hence saccadic chronostasis will disappear in the third phase of the experiment when assessed alongside tapping (shown in Figure 5.1). It is also possible that no discrepancy is perceived or that the perceptual system dominates consciousness, such that the illusion is still obtained in this final stage despite concurrent and inconsistent motor behaviour.

Methods

Participants. 10 subjects completed the experiment (7 male, mean age 27.2, SD 5.9).

Apparatus. Subjects sat before a 14” CRT colour monitor refreshing at 60 Hz. Eye to screen distance was maintained at 59 cm using an adjustable chin rest. Horizontal eye movements were recorded using AC electro-oculography (D150 amp: Digitimer; band pass filtered 0.032-30 Hz) and sampled at 200 Hz. Electrodes were placed on the outer canthus of each eye. Taps of the dominant index finger were recorded using a force-sensitive plate (strain gauge: built in house) and also sampled at 200 Hz. The plate was set atop a response box and placed at a comfortable position in front of the subject, with additional wrist support provided where necessary. It was
approximately 1.5 cm wide and 4 cm long. Visual stimuli were black on a white background, subtending approximately 0.5°. They consisted of a cross and/or a digital counter, initially set to “0” and counting through the digits “1” to “4”. The experiments were controlled by a PC interfaced with a 12 bit A/D card (National Instruments DAQ 1200).

**Design.** A repeated-measures design was employed with two conditions (saccade and a constant fixation control) and three phases. The first phase occurred in a separate block type in which saccadic chronostasis was initially quantified. Subjects completed one, two or three such blocks per condition (see procedure below). The second and third phases occurred in a single block type that incorporated a tapping task. Again, subjects completed one to three blocks per condition. Block order was counterbalanced, with subjects receiving one block from each condition in alternation until phase one was complete, then moving on to receive one block from each condition in alternation for the phase two/three blocks.

**Procedure.** In phase one saccade blocks, subjects fixated a cross on one side of the screen while a target “0” was displayed on the other side. The trial was initiated with a press on the tapping plate. Subjects then made a voluntary 24° saccade towards the “0”, with eye movement triggering a change of digit to a “1” when the saccade had travelled one fifth of the distance to target. The “1” remained on screen for 400-1600 ms; subsequent digits (“2”,“3”) remained on the screen for 1 second 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. Saccade start/end points were calculated automatically using a velocity criterion; difference values between sample n and sample n-3 were compared to thresholds based on background signal noise. Trials where the first saccade recorded did not exceed 90% of the total distance recorded (summed across all detected saccades) were excluded on-line and repeated immediately. Phase one control (constant fixation) blocks were similar, except that
subjects simply fixated a "0" at equivalent eccentricity that changed to become the judged digit ("1") 500 ms after the subject pressed the tapping plate.

Initially, the duration of the "1" was controlled by a MOBS procedure (low boundary 400 ms, high boundary 1600 ms, initial presentation random 800-1200 ms, five reversals to terminate). Following its termination, the block concluded with five further trials, identical to the earlier ones except that the response option "same as" was available in addition to "less than" and "greater than". These trials were included to check the legitimacy of the MOBS value that had been derived. They used first interval ("1") durations that were based on the previous MOBS termination value/values. For the first six subjects, the MOBS termination value from the current block was added to one of five offsets (-250, -125, 0 125, or 250 ms) with the five trials presented in random order. Following a slight procedural change, the final four subjects had the same five offsets added to the mean of all MOBS termination values acquired thus far for that condition (i.e. for a second phase one saccade block, the mean of the first and second blocks MOBS termination values was used). If this validation procedure yielded the correct pattern of judgements after a single block, subjects were not required to complete a second block. Otherwise, they went on to complete a second block before continuing to the next phase for that condition. Patterns were judged correct when the subject responded either <, <, =, >, > or <, =, =, > to the offset values -250, -125, 0, 125, 250 respectively. When time permitted, some subjects received a third block following incorrect pattern matching in the second block. Direction of saccade (saccade conditions: left to right and vice versa) or position of the counter (control conditions: left or right) alternated every trial. In both phase one conditions blocks were of variable length, typically 11-25 trials.

Phase two/three blocks began with ten trials involving only tapping (phase two). The sequence of stimuli relative to an eye movement (or relative to trial initiation for control blocks) was identical to than presented in phase one, except that the first post-saccadic interval (the "1") was
maintained at a constant duration. For the first six subjects, this value was set to the MOB termination value for their final phase one block from the appropriate condition (control or saccade). For the final four subjects, it was equal to the mean of all phase one MOB termination values for the appropriate condition. Subjects were instructed that once the “1” appeared on screen (control condition) or was seen following a saccade (saccade condition) they were to tap nine times at a rate of three taps per second, such that their third, sixth and ninth taps coincided with the change of counter digits from “1” to “2”, “2” to “3” and “3” to “4”. No decision was required about the length of the first interval, which they were told was constant. For a given run of nine taps, onset times were calculated automatically. The largest value recorded across the nine taps was divided by ten and added to the baseline (no plate contact) value for that run. A tap was considered to have occurred when this threshold was crossed in a positive direction.

Phase three trials occurred immediately following ten successful phase two trials. They were identical to phase one trials, with first interval duration varying according to a MOBS, except that the subject was additionally required to tap (as in phase two). They were told that they should try to adjust their taps following the counter change form “1” to “2”, given that they could not predict when this would occur. When the MOBS terminated, five test trials were presented (as in phase one), with an incorrect pattern on the first phase two/three block in a given condition meaning that another such block was completed, and, occasionally, a third block. Subjective second estimates in phases one and three (with and without tapping) were derived as the mean of all MOBS termination values in each condition (usually two). In the saccade conditions, each estimate was corrected post hoc to match the time the “1” was on screen following target foveation by subtracting the average time the eye was in motion following the triggered change of digit (averaged across all blocks in each saccadic phase). Because tap onset times were also initially calculated relative to the point the counter changed to display a “1”, the same
correction was applied to these values, yielding tap time relative to saccade target foveation. The experiment took around 50 minutes to complete.

Statistical analyses. Subjective seconds were analysed in a 2 x 2 repeated measures ANOVA, comparing control and saccade conditions with/without tapping. Mean tap onset time was calculated separately for the first and final set of three taps within phase two tapping epochs, to give a fine-grained index of adjustments in tap onset times over trials. Automatically recorded tap times were inspected and trials removed in which the algorithm had returned values that were clearly inconsistent with the task. Because subjects often took a few trials to get to grips with the tapping task when initially presented with it, the first trial recorded and validated in this way was often not the first trial of a particular phase two epoch. This was problematic given the importance of possible motor errors early in performance (based on motor expectations) that might disappear as subjects changed their tapping patterns to conform with the stimuli presented to them. For this reason, when subjects had completed two or more phase two/three blocks in a given condition (true for 8/10 subjects in the control condition and 9/10 subjects in the saccade condition) only taps recorded in their final block were used. The task was well understood enough at this point for early trials to be completed successfully, but the subjects had just completed a block from the alternative condition, so it was hoped that expectations about the first interval duration would be effectively reset.

Results and discussion

Saccade characteristics. Saccades took an average of 81 ms in phase one blocks, compared to 82 ms in phase two/three blocks.

Time estimates. Figure 5.2 shows mean corrected time estimates across subjects for control and saccade conditions prior to and concurrent with the tapping task. Control matches are a little low, but more striking is the
substantial reduction in subjective seconds for the saccade conditions. It appears that saccadic chronostasis occurs both prior to and during tapping, a conclusion that is supported by the results of a two-way ANOVA that revealed a main effect of eye status (control compared to saccade; $f = 8.081$, df = 1,9, $p = 0.019$) but no main effect of experimental phase and no interaction.

**Phase 2 (tapping) data.**

Figure 5.3 shows the mean time at which subjects made each of their nine taps early and late in phase two of their final tapping block. The upper panel shows data for the control condition, in which the counter’s digit changes were presented, on average, at 941 ms, 1941 ms and 2941 ms. Subjects were able to match these change times well with their third, sixth and ninth taps right from the beginning of a tapping session; both early and late tap patterns are accurate, differing little from one another. Taps occurring between counter changes were orderly, with the overall pattern of means being well fitted by linear regression (early: tap time = $325(tap) - 7$, $r^2 = 0.999$, $p < 0.001$; late: tap time = $332(tap) - 31$, $r^2 = 0.999$, $p < 0.001$). With close inspection, there seems to be a slight deviation from strict linearity, with the slope of the function increasing a little between the third and fourth taps, and again between the sixth and seventh taps. It seems likely that this

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1 The value of the average first presentation time, 941 ms, differs slightly from the value shown for the control subjective second in Figure 4.2 (944 ms). This is because for the first six subjects the time the “1” was displayed in phase two was determined by their final
pattern reflects the effect of attempting to tap in triplets, with the third and sixth taps aimed to coincide with a counter change and receiving emphasis. Hence a slight delay occurs before initiating the next triplet. This effect is also observable for the first tap; although it does not follow a beat, it arrives slightly late, yielding a slope from the first to third taps that is similar to those found for fourth to sixth and seventh to ninth taps.

For the saccade condition (lower panel) tap patterns completed early and late in a given phase two session are shown along with a hypothetical predicted pattern based

**Figure 5.3.** Mean contact times (ms) averaged across subjects for a pattern of nine taps, every third tap produced in synchrony with a visual counter change. Data are shown separately for control and saccade conditions, and for the first three / last three taps of the final phase two session. Average counter change times appear at the bottom of each plot.

phase one block termination value rather than as an average of all phase one block termination values.
upon saccadic chronostasis occurring immediately after eye movement and influencing tap times. This predicted pattern was produced by assuming a tap rate of 333.3 ms and successful anticipation of the first counter change (on average occurring after 810 ms). It is essentially identical to the situation depicted in the left-hand side of Figure 5.1 earlier, in which a common clock underlies time judgements and tap production and is influenced early on by saccadic chronostasis. This prediction is not well matched by the data. Where in the control condition subjects were accurate in timing their third tap to coincide with the digit change from “1” to “2”, here they are clearly late. Although the predicted pattern does not take account of the slight deviations from linearity observed for triplet production in the control condition (and again here in the saccade condition) this does not effect the prediction for the onset time of the third tap. To test the reliability of subjects’ late third tap production, each subject’s individual presentation interval (the time at which the change from “1” to “2” occurred during phase two) was subtracted from their average contact time for this tap. Positive values indicate late tap production, negative values early tap production. The mean of these tap asynchrony values differed significantly from zero for third taps produced both early and late in phase two sessions (early: asynchrony = 109 ms, t = 3.452, df = 9, p = 0.007; late: asynchrony = 130 ms, t = 3.255, p = 0.01). This highlights another important feature of the data. Subjects did not alter their tap times over the course of their ten tapping trials, but continued to come in late on their third taps. It appears that both early and late in phase two subjects simply accelerated their tapping rate slightly across the entire pattern so that the error on the first tap was compensated for by the ninth tap. This suggestion is confirmed by linear regressions applied to the mean tap time data (early: tap time = 312(tap) + 12, r^2 = 0.999, p < 0.001; late: tap time = 308(tap) + 19, r^2 = 0.999, p < 0.001) which show lower slopes relative to the control conditions. In addition to being inconsistent with the proposal that saccadic chronostasis would affect tap production rapidly after a saccade (the prediction shown in Figure 5.3) these data are also inconsistent with the
variant idea presented in the introduction in which the effect is spread over the first three taps. Here also, the third tap would not be predicted to arrive late. In fact, the pattern of tapping for the first three taps in a sequence of nine (those produced in the absence of corrective feedback from the counter changes) is very similar in the control and saccade conditions. A $2 \times 2 \times 3$ ANOVA was used to assess differences between saccade and control conditions (factor one) and early and late taps sequences (factor two) for the first three taps of a sequence (factor three, three levels). Only the rather trivial main effect of factor three was significant ($f = 1092.447$, $df = 2,18$, $p < 0.001$).

Combining the tapping data from phase two of the experiment with the subjective second estimates from phases one and three, the following summary emerges:

1) Prior to tapping, subjects experienced saccadic chronostasis when making temporal judgements about the duration of a “1” seen after an eye movement.

2) Subjects were next required to tap triplets in synchrony with the changes of the counter that had just been judged to yield a sensation of equal duration for the “1” and later digits (but in which the “1” was in fact on screen for less time). Subjects reliably came in late for the first change, producing a pattern over the first three taps that was very similar to that found in the control condition, i.e. as if saccadic chronostasis was not affecting their tapping behaviour. They failed to adapt their tapping rate to better synchronise with counter changes, as evidenced by a very similar pattern emerging for taps early and late in a phase two session (although the ten trials experienced may have been insufficient to induce such a change).

3) When subjects went on to perform the tapping and judgement tasks together, they continued to experience saccadic chronostasis for the judgement task. The concurrent performance of the tapping task,
apparently uninfluenced by saccadic chronostasis, failed to provide information capable of overruling the illusion.

What, then, does this pattern suggest about the independence of the timing processes underlying the motor act of tapping and the perceptual act of judging the duration of a visual stimulus? Taken at face value, the tapping data suggests that motor and perceptual timing are dissociated for the tasks used here, being independently affected by saccadic chronostasis. Not only are they dissociated, they appear to be mutually impenetrable in the sense that each is unable to use information employed by the other process, even when the tasks are performed together. Persistent errors in motor production did not prevent subjects from once again settling on a first interval that was too small, while saccadic chronostasis failed to adapt motor performance to produce initial taps earlier on. Hence neither timing process could be employed to calibrate the other. This picture may at first appear incompatible with previous work suggesting a common basis for perceptual and motor timing (e.g. Keele et al, 1985). However, the fact that motor and perceptual tasks display correlated performance measures and are similarly affected in neurological disorders implies only a common type of clock (in terms of functional parameters and neural localisation), not necessarily a single timer. Ivry and colleagues, for example, have suggested a “multiple timer” model to account for improved performance in bimanual compared to unimanual tapping tasks (Ivry and Richardson, 2002). If separate clocks exist to be employed by multiple effectors and/or sensory mechanisms, it would make sense that they should proceed independently from one another to avoid crosstalk problems when multitasking. The pathway by which saccadic chronostasis is produced for duration judgements about visual stimuli could easily be specific to one member of a flexible class of mental timers that operate in a fundamentally similar but mutually shielded manner.

This interpretation needs to be qualified, however. Regarding the proposed mutual impenetrability of the two systems, it is possible that the
discrepancy between them was simply too small to notice, amounting as it did to only 100 or so ms. With larger discrepancies, corrective mechanisms might have been brought into play. There is an issue here regarding the instruction used. Subjects were told to try and synchronise with the counter changes, but there was nothing in the way of incentive for maximising accuracy and attention was not specifically directed to the first post-saccadic counter change. It is interesting to note that the alternative pattern of results that might have been obtained, had saccadic chronostasis influenced early tapping times, is open to differing interpretations. Most notably, rapidity of motor adaptation might have yielded such a pattern. A striking feature apparent in these data is the motor system's failure to adapt to the actual presented duration (at least over only ten trials). Difficulties surrounding how to assess motor expectations and the effects of practice make research of this type methodologically challenging, but it seems reasonable to conclude that the present experiment provides initial support for the notion that saccadic chronostasis affects only a limited subset of timing mechanisms.

**Experiment 4b**

When saccadic chronostasis occurs, the brain seems to stretch the perception of a post-saccadic percept backwards in time (as measured by its perceived duration). Isolated perceptions, however, exist within the context of other sensory events, with which they must be temporally integrated to produce a sensation of simultaneity or succession and the passage of time. What is the relationship between the actual time of occurrence of individual sensory events and their perceived ordering? The issue has been addressed within the temporal-order judgement paradigm (briefly reviewed in Chapter 1). Here, two sensory events are presented in near temporal proximity and the observer is required to judge either 1) which occurred first or 2) whether they appeared simultaneously. Humans show high temporal sensitivity, able to discriminate the order of two spatially displaced stimuli 75% of the time.
with temporal offsets of 30 ms or less. This level of sensitivity arises regardless of stimulus modality, in contrast to judgements about successiveness versus simultaneity for rapidly repeated identical stimuli (Hirsh and Sherrick, 1961). Furthermore, a number of factors have been shown to result in biases, yielding points of subjective simultaneity (PSS) that differ from a physical zero millisecond offset (actual simultaneous presentation). Examples include modality differences (e.g. sound and light; Stone, Hunkin, Porrill, Wood, Keeler, Beanland, Port, and Porter, 2002), attentional allocation (prior entry; e.g. Shore, Spence, and Klein, 2001), stimulus intensity, temporal profiles and a range of other factors (Jaskowski, 1999).

Temporal order judgements have also been investigated for combinations of sensory and motor events. McCloskey and colleagues (McCloskey, Colebatch, Potter, and Burke, 1983) used very brief tactile electrical stimulation to the ankle presented around the time subjects made a voluntary movement. Individual subjects made contractions primarily involving a single muscle, but a range of movements were studied across subjects, including those of the foot and jaw. Subjects judged the onset of a movement to be synchronous with the shock when EMG activity actually preceded the shock by 40-320 ms. They were, however, capable of differentially judging the moment of their internal instruction to begin movement (their conscious decision). This was judged to precede the onset of EMG by up to 100 ms. While the finding that a conscious decision to move is judged to have arisen before actual movement is typical (see also Libet, Gleason, Wright, and Pearl, 1983; Haggard and Eimer, 1999) the movement onset result is more contentious. Haggard, Newman, and Magno (1999) for example, report an anticipatory (as opposed to delayed) awareness of movement initiation that scales with the complexity of the movement pattern. They used a Libet clock paradigm in which movement onset (the time at which a key had been pressed) was judged relative to the position of a rotating on-screen clock hand. Similarly, Dassonville (1995) required subjects to judge when a tactile stimulus delivered to the index
finger occurred relative to a horizontal (left to right) arm movement. Anticipatory awareness was reported for both the time of movement onset and for the time of movement termination. Differences between EMG and button press onset times are not sufficient to explain the discrepancy in both cases, although modality and attention effects might be (this issue is considered for the current experiment later in the discussion section).

In an even more striking series of investigations, trains of stimulation applied directly to the somatosensory cortex of neurosurgical patients took around 200 ms to cross a threshold of awareness ("neuronal adequacy") and were judged to be delayed relative to peripheral (skin) stimulation. By contrast, trains applied to the medial lemniscus, which also had to be presented for around 200 ms to reach conscious awareness, were correctly judged as synchronous with peripheral stimulation (Libet, Wright, Feinstein, and Pearl, 1979). The authors concluded that the initial evoked response in primary sensory cortex (present for stimulation in the periphery and medial lemniscus but not somatosensory cortex) acted as a time marker despite being inadequate to produce conscious experience in itself. Subsequent awareness arising from ongoing cortical stimulation was referred back to this event.

The studies reviewed in Chapter 2 investigating observers’ temporal perception of visual stimuli around the time of saccades clearly belong within this tradition, being a rather complex mixture of temporal order judgements for sensory and motor events. To recap, when subjects were asked to judge whether a horizontal sinusoidal test grating presented for 5 ms in the area traversed by a 6° saccade arrived before, during or after the eye movement a complex pattern of results emerged (Volkmann and Moore, 1978). For stimuli presented after the onset of the saccade (with only the “during” and “after” responses available) two observers showed a strong bias towards judging the stimulus to have arrived during the saccade. For the single observer tested with stimuli also occurring prior to the saccade (and additionally given the “before” response option) these stimuli where also judged to have occurred during the saccade more often than would be
expected. Stimuli that arrived during the saccade where typically judged to have arrived before it, so times of occurrence for these stimuli were not simply drawn inwards towards the saccadic event.

Some years later, Deubel and colleagues (Deubel, Irwin, and Schneider, 1999) had subjects make either reactive or delayed saccades to a peripheral target (6° in both cases). An open circle appeared on screen for 20 ms at a time ranging from 450 ms before the saccade to 250 ms after it. The circle was located at one of three locations: the initial fixation point, the saccade target point, or the opposite point (the alternative saccade target). Six subjects judged whether their gaze had been on the central fixation point or the saccade target point when the circle appeared. They often incorrectly felt that they were already looking at the saccade target even when the circle appeared well before their saccade. The effect was less marked when the circle appeared opposite the target, and nearly absent when it appeared at the initial fixation point. However, in these experiments the whole psychometric curve was simply shifted towards negative circle-saccade asynchronies. Subjects showed no tendency to claim that they were still looking at the central fixation point when the circle appeared after their saccade, failing to replicate the over-attribute of post saccadic stimuli to the “during” category in Volkmann and Moore’s experiments.

An important question here is what exactly the subjects were attempting to do in these experiments. If we assume that chronostasis causes the onset of the post-saccadic image to be predated to before saccade initiation, we might expect that stimuli flashed before or during the saccade would be mistakenly considered to have occurred simultaneous with or after this event, shifting the psychometric curve. This expectation is supported in the work of Deubel and colleagues, perhaps suggesting that when these subjects were asked where their gaze had been when the circle appeared, they made a judgement about whether they could see the target stimulus yet. In this sense they were not asking, “what are my eyes doing?” but rather, “what can I see?” By contrast, Volkmann and Moore’s subjects may have been attempting to align their sensation of their own eye movement with the
visual stimulus. In this case, we might expect awareness of movement initiation to be delayed (as demonstrated in McCloskey et al., 1983, but see also Haggard, Newman, and Magno, 1999) resulting in stimuli presented after the eye movement being falsely placed into the “during” category. Hence attending to states of movement and states of visual perception might yield opposite effects and resolve the apparent contradiction in results.

Deubel et al.'s results suggest that chronostasis may be reflected in judgements about instantaneous visual events. If we envisage a unitary system in which time alignments between different sensory modalities must be fitted coherently into an overall conscious perception, it seems reasonable that not just visual but all sensory events should be misaligned relative to the initial perception of a post-saccadic stimulus. Stimuli presented during a saccade should be perceived to have occurred after the subject first saw the saccade target. Experiment 4b tested this prediction using tactile stimuli.

Methods

Participants. 10 subjects completed the experiment (8 male, mean age 28.9, SD 6.1). 4 had previously participated in experiment 4a.

Apparatus. Subjects sat before a 14” CRT colour monitor refreshing at 60 Hz. Eye to screen distance was maintained at 60 cm using an adjustable chin rest. Horizontal eye movements were recorded using AC electro-oculography (D150 amp: Digitimer; band pass filtered 0.032-30 Hz) and sampled at 200 Hz. Electrodes were placed on the outer canthus of each eye. Electrical stimulation was delivered via two ring electrodes placed on the index finger of the left hand. A 200 µs pulse was produced using an isolated constant current stimulator (Digitimer DS2A) with stimulation level set for each subject so as to be easily perceived but not uncomfortable. Visual stimuli (two crosses) were initially black on a white background, subtending
approximately 0.5°. The experiments were controlled by a PC interfaced with a 12 bit A/D card (National Instruments DAQ 1200).

**Design.** A single experimental condition was employed in which subjects judged whether they felt a tactile stimulus before or after their gaze reached its target. Each subject completed sixteen to twenty blocks of ten trials each.

**Procedure.** Subjects fixated a cross on one side of the screen while a target cross was displayed on the other side, then initiated the trial with a mouse key press. After a random delay of 400-1000 ms, the cross they were fixating changed to become red, signalling that they should make a speeded 22° saccade towards the target cross. Tactile stimulation was delivered at a random time relative to a given subject's average reaction time for the previous block (arbitrarily set at 200 ms for the first block). These random offset values were generated on each trial in the range -80 to +160 ms. Hence stimulation was centred upon the region from around 80 ms before to around 80 ms after a saccade (assuming an 80 ms saccade). Subjects indicated whether the tactile stimulus occurred before or after their gaze arrived at target. Saccade start/end points were calculated automatically using a velocity criterion; difference values between sample n and sample n-3 were compared to thresholds based on background signal noise. Trials where the first saccade recorded did not exceed 90% of the total distance recorded (summed across all detected saccades) were excluded on-line and repeated immediately. On each trial, the time of tactile stimulus delivery was calculated relative to the point of saccade completion (negative values indicating stimulation before the end of the saccade). Direction of saccade alternated every trial. The experiment took around 45 minutes to complete.

**Statistical analyses.** Points of subjective simultaneity (PSS) were calculated for each subject using logistic regression, with time of tactile stimulation as the independent variable and response (before/after) as the dependent variable (see Experiment 1a for further details).
Results and discussion

Saccade characteristics. Saccades took an average of 78 ms, and were initiated with an average reaction time of 258 ms.

Points of subjective simultaneity. Across subjects, the mean PSS was 8.1 ms (standard deviation 49.8). This value did not differ significantly from zero (p > 0.05) indicating that subjects were accurate in localising the time at which they had received tactile stimulation relative to the time their eyes reached the target. The unitary sensation hypothesis, in which sensory events across modalities are influenced by saccadic chronostasis, predicts a substantial negative PSS and is not supported. Four possible interpretations of this negative result are discussed below.

Tactile/visual latency differences counteract the predicted result. Tactile afferent information is transmitted more rapidly than visual information (at least in terms of the first detectable cortical EEG components; O'Boyle, 1999). If this advantage is reflected in visual/tactile PSS estimates, such that visual stimuli must be presented before tactile stimuli to be judged simultaneous with them, it is possible that the hypothesised rightwards shift did occur in the present data but was counteracted by an equal and opposite latency-dependent leftwards shift. The absence of an appropriate control condition makes direct assessment impossible, but results in previous temporal order judgement research offer partial support for this interpretation (Hirsh and Sherrick, 1961; Spence, Shore, and Klein, 2001). In the absence of specific manipulations of attention and when all stimuli are well above threshold, visual stimuli must typically be presented around 30 ms before tactile stimuli to be judged simultaneous. This PSS bias varies with factors such as the nature of the question that is being asked, the spatial separation of the stimuli and the side of space in which each is presented, such that the most extreme combinations of task conditions (visual stimulus
on the right side of space, tactile on the left, making a left/right judgement about which came first) may yield a PSS of 70+ ms (Spence, Shore, and Klein, 2001). Even more extreme values can arise when attention is diverted to the tactile modality. Based on the studies reported previously in Chapters 2 and 3, a PSS shift equal to the typical effect size of chronostasis would be anticipated, around 130 ms for an 80 ms saccade. Deubel, Irwin, and Schneider (1999) report an effect of 100 to 250 ms for visual targets judged relative to gaze position. Hence the tactile/visual PSS shift would have to be unusually large in the current experiment to account for the null result, but cannot be ruled out. Any replication should therefore include a control condition in which a tactile stimulus in judged relative to the onset of a visual stimulus.

**Saccadic chronostasis does not arise for reactive saccades.** The experiments reported in previous chapters have demonstrated saccadic chronostasis only for voluntary saccades, not reactive ones like those used here in order to permit some degree of control over the timing of the tactile stimulation. Although Deubel et al. also used reactive saccades and found an effect consistent with saccadic chronostasis for visual stimuli, there is a procedural difference; they employed saccades to a sudden visual onset, whereas the current experiment employed saccades triggered by a central visual cue. This issue is dealt with later (in Chapter 6). To pre-empt its results, saccadic chronostasis can in fact be demonstrated for reactive saccades of both types described here, so this problem is unlikely to have lead to the current negative result.

**Multisensory temporal perception is not unitary.** Taken at face value, it appears that while chronostasis may extend the perception of the post-saccadic target backwards, this extended percept is not available for comparisons with stimuli presented in the tactile modality. An illusory perception evidenced by a subsequent temporal estimation bias fails to influence the system that is time-tagging the electric shock. In this sense, the
conscious perception that the system settles upon smoothes over contradictions to provide the post-hoc feeling of consistency. The results of Deubel et al. suggest that saccadic chronostasis is important when estimating the time of occurrence of visual events (not surprising perhaps, given that this is the sensory modality that is being manipulated). An interesting question emerges as to what would happen if both visual and tactile events were presented near the time of a saccade, with temporal order judgements made between each pair. Would the brief visual events, apparently integrated with the illusory perception seen in chronostasis, and the tactile event, apparently not so integrated, appear to occur at different times?

Subjects didn’t do what they were supposed to do. Perhaps the most telling objection to the previous interpretation is the distinction drawn earlier between judgements about movements and judgements about perceptions. It was suggested that Deubel et al. directed their subjects to make judgements relative to what they could see (i.e. the perception of the saccadic target or otherwise) rather than their current movement state, inducing appropriate conditions for saccadic chronostasis to influence judgements. Here, a question similar to theirs was deliberately employed (relating to the direction of gaze) but the form was different. Deubel et al. asked where gaze was directed when a visual event occurred; in the present experiment, subjects were asked whether the tactile event occurred before or after gaze was directed to a particular point. The difference may be important given the likely fragility of any instruction to adopt a particular strategy. Neither Deubel et al.’s question nor the one adopted here are ideally suited to focus attention on the post-saccadic percept, but it may be that Deubel et al. were successful in doing so where the present experiment was not. It is not currently clear how subjects would be expected to respond if they had focussed on their movement, but a veridical response is not unreasonable. McCloskey et al (1983) found a bias to report a tactile stimulus occurring after EMG-defined movement initiation to be coincident with it, but did not
investigate the time at which a movement was considered to have
terminated. Dassonville (1995) found that tactile stimuli delivered towards
the end of a movement were often misjudged to have occurred after it had
been completed, but he employed movements of the arm, not eye. The issue
would be best resolved by a partial replication in which different groups of
subjects received different instructions. The post-saccadic target should
change form mid saccade (as in the standard chronostasis paradigm) with
one group of subjects reporting whether the tactile buzz occurred before or
after they first saw this post-saccadic form. A second group should be asked
whether the buzz occurred before the end of their eye movement and
encouraged to ignore visual cues. In this way this objection could be more
fully assessed.

General discussion

In Experiment 4a, subjects were required to tap synchronously with
counter changes that were perceived to be equally spaced (as determined in
previous blocks without tapping) but were in fact unequal (the result of
saccadic chronostasis). They persistently tapped late for the first counter
change, indicating that the timer controlling their tapping behaviour had not
been influenced by saccadic chronostasis. Furthermore, when saccadic
chronostasis was reassessed in the presence of concurrent tapping, it
emerged again, indicating that the veridical timing information employed to
tap repetitively could not be used to override the illusion. In Experiment 4b,
subjects were required to judge whether a tactile stimulus applied to the
index finger occurred before or after their gaze arrived at the target of a
centrally cued reactive saccade. They were able to do so accurately, at least
on average. Assuming that they had judged the tactile event relative to the
onset of the post-saccadic percept, this result implies that a backwards
extension of this percept did not influence its apparent temporal relationship
with the tactile stimulus.
The former result suggests that separate timers for perception and motor action may be differentially influenced by this temporal illusion, each unable to influence the other. This is a striking dissociation. As previously discussed, it does not necessarily imply different types of timer, or different neural substrates, only that the individual timers themselves are not identical. The latter result suggests one of the following. Firstly, chronostasis might affect the feeling of accumulated time (evidenced in the standard paradigm) without actually influencing the perception of when a stimulus began. This is an interesting dissociation, but the results of Deubel, Irwin, and Schneider (1999) suggest that it may not be the case. Secondly, saccadic chronostasis might influence temporal order judgements for visual stimuli, but not for stimuli in other modalities (i.e. touch). These events are subsequently slotted into overall temporal perception in a manner that reflects their actual relationship to fully resolved visual events.

These interesting conclusions suffer from the same methodological shortcoming, relating to what exactly subjects were attempting to do in the respective tasks. Particularly for Experiment 4b, the results may be explained by subjects' failure to make the desired comparison between the post-saccadic image's onset time and the tactile stimulus. However, the evidence is at least suggestive that chronostasis does not affect all aspects of timing nor reset the time of perceived image onset for all manner of temporal comparisons. Such dissociations imply that the conscious experience of temporal processes may not be a unitary phenomenon, in line with the multiple drafts model proposed by Dennett and Kinsbourne (1992).
Chapter 6. Manipulations of saccade type and post-saccadic stimuli

The experiments reported in Chapters 2 and 3 required subjects to make a voluntary saccade to a target that maintained its post-saccadic form for a period approaching one second, then changed discretely like the second hand of a clock. It would be interesting to know whether the illusion of chronostasis is obtained when these rather specific conditions are altered. In Experiment 5a the duration of the post-saccadic stimuli and their precise form (an unspaced sequence of four discrete digits) are altered. These changes constitute an attempt to falsify the current working hypothesis (that the post-saccadic image is predated to a point prior to movement onset) and permit an initial characterisation of the illusion within the framework of internal clock models of human prospective duration judgement. In Experiments 5b and 5c the nature of the saccade made by subjects is changed, permitting inferences to be drawn about the level at which chronostasis operates within the brain.

Experiment 5a

Despite being four decades old, the internal clock model (reviewed in Chapter 1 and schematically presented in Figure 1.1) remains the most widely discussed information-processing model of human and animal timing behaviour. Illusions of timing are also not new, with a number of non-temporal factors known to influence perceived duration. Examples include order-specific biases for interval judgements (Hellstroem, 1985), increasing perceived duration with availability of attentional resources (Burle and Casini, 2001) and effects of numerous qualities of the to-be-judged temporal stimulus. There have been various attempts to map the influence of such factors onto the components of the hypothesised internal clock (e.g. Franssen and Vandierendonck, 2002, Wearden and Culpin, 2002). The model can accommodate a shift in the mean perceived duration

130
of a stimulus by adjusting the function of any one of a number of its
components. Influences on some of these components are characterised by a
mean duration shift effect that scales with the duration that is being judged,
while some imply a shift that is constant across durations. To give one
example, manipulations thought to affect the speed of the pacemaker (such
as the arousing effect of a train of clicks; Treisman, Faulkner, and Naish,
1990) produce a larger effect for longer duration stimuli because the number
of pulses accumulated is equal to rate multiplied by time. Wearden,
Edwards, Fakhri, and Percival (1998) made use of this fact to help infer the
component responsible for the commonly reported finding that sounds are
judged to be longer than lights of equivalent duration. They demonstrated
that this effect also scaled with stimulus duration, and interacted with the
effect of a train of clicks in a manner that suggested that differences in
pacemaker speed were also critical to the sound/light misperception.

The hypothesis that the post-saccadic image is being predated to a
point prior to movement onset can be usefully considered within this
framework. It clearly implies that the effect size of chronostasis should be
constant across changes in the duration of the post-saccadic stimulus (in
every case, the length of the eye movement plus some additional constant
quantity is simply added to the perceived duration of the stimulus). If this
proves to be the case, the number of clock components of potential
importance for chronostasis is substantially reduced. If, on the other hand,
an effect that increases proportionally with stimulus duration is found, the
simple predating hypothesis is undermined and alternative clock
components (such as the pacemaker) become candidates for mediating
chronostasis.

If a number of different post-saccadic stimulus durations are
employed, the contrast drawn so far between a constant versus a
multiplicative effect of stimulus duration upon the magnitude of
chronostasis may be supplemented with a prediction of a specific deviation
from one or other pattern. It was demonstrated in Chapter 3 that the
perceived continuity of the saccade target object across a saccade can have a
profound effect upon the experience of chronostasis. It was suggested that the brain assumes the constancy of the post-saccadic image, but that this assumption may be overridden in certain circumstances. It seems plausible that the saccade target might have to be perceived for some minimum duration before the assumption of constancy is applied. In this case, an additive (constant) or multiplicative (proportional) pattern for higher stimulus durations might be supplemented by a complete absence of chronostasis below some critical post-saccadic stimulus duration. A second consideration relates to the all or none nature of the dichotomy drawn thus far between additive and multiplicative effects. It is possible that both coexist, or that a multiplicative effect does not influence the full duration of the post-saccadic stimulus and/or also influences the comparison stimulus (e.g. for a general process such as arousal). For these reasons, four stimulus durations were employed in Experiment 5a, ranging from 333 to 1333 ms.

Experiment 5a was also designed to test another prediction arising from the hypothesis of post-saccadic image backdating but unrelated to the internal clock model. If the post-saccadic image of an object or scene is having its duration extended under conditions of chronostasis, the nature of the temporal comparison should make no difference. Specifically, the comparison stimuli employed in previous experiments (the digits of an advancing digital counter) should be able to be swapped with an alternative reference without affecting the illusion. Consequently, the “0,1,2,3,4” sequence used previously was replaced with a target cross that changed to display an unfilled circle mid-saccade. The circle was briefly blanked, then reappeared a single time to act as the reference stimulus.

Methods

Participants. 10 subjects (5 male, mean age 27.9, SD 7.8) completed Experiment 5a.
Apparatus. Subjects sat before a 22" CRT colour monitor refreshing at 60 Hz. Eye to screen distance was maintained at 41 cm using an adjustable chin rest. Horizontal eye movements were recorded from the left eye using an infra-red eye tracker (Microguide 1000 spectacles, low-pass filtered at 40 Hz) and sampled at 200 Hz. Stimuli were black or red on a white background, subtending 1.1°. They consisted of crosses and open circles. The experiments were controlled by a PC interfaced with a 12 bit A/D card (National Instruments DAQ 1200).

Design. A two factor (2 x 4) repeated-measures design was employed. The first factor eye status compared a voluntary saccade of 20° to constant fixation at matched eccentricity (±10°). The second factor stimulus duration varied the length of the comparison stimulus across the following values: 333 ms, 667 ms, 1000 ms, 1333 ms. Trials from each of the eight conditions were presented in separate blocks. Four constant fixation blocks and four saccade blocks were completed at each level of stimulus duration for a total of 32 blocks. Each subject received these blocks in a random order.

Procedure. In saccade blocks, subjects fixated a red cross on one side of the screen, initiated the trial with a mouse key press then made a voluntary saccade towards a black cross on the far side of the screen. Eye movement triggered the black cross to be replaced with a circle when the saccade had travelled one fifth of the distance to target. The circle remained on screen for a variable duration, within limits determined by the current comparison stimulus duration (see table 6.1). It then disappeared, to be replaced by an identical circle (the comparison stimulus) after 500 ms. Subjects indicated whether the time they saw the first circle was longer or shorter than that for which the comparison circle was displayed. The duration of the first circle was controlled by a MOBS procedure (five reversals to terminate). Parameters of the MOBS that varied across levels of stimulus duration are presented in table 6.1. Blocks finished when the MOBS had terminated.
### Table 6.1. MOBS parameters for stimulus duration levels of Experiment 5a

<table>
<thead>
<tr>
<th>Stimulus duration</th>
<th>Low boundary</th>
<th>High boundary</th>
<th>Initial presentation random in the range:</th>
</tr>
</thead>
<tbody>
<tr>
<td>333 ms</td>
<td>67 ms</td>
<td>600 ms</td>
<td>267 - 400 ms</td>
</tr>
<tr>
<td>667 ms</td>
<td>133 ms</td>
<td>1200 ms</td>
<td>533 - 800 ms</td>
</tr>
<tr>
<td>1000 ms</td>
<td>200 ms</td>
<td>1800 ms</td>
<td>800 - 1200 ms</td>
</tr>
<tr>
<td>1333 ms</td>
<td>267 ms</td>
<td>2400 ms</td>
<td>1067 - 1600 ms</td>
</tr>
</tbody>
</table>

Saccade start/end points were calculated automatically using a velocity criterion; difference values between sample n and sample n-3 were compared to thresholds based on background signal noise. Trials where the first saccade recorded did not exceed 90% of the total distance recorded (summed across all detected saccades) were excluded on line and repeated immediately. In control (constant fixation) trials, subjects initially fixated a cross at equivalent eccentricity. It was blanked 400 ms after the subject’s mouse key press, then replaced after a further 100 ms by the to-be-judged circle, with subsequent stimulus presentation and subject responses as per saccade trials. Direction of saccade (saccade conditions: left to right and vice versa) or position of the fixation cross (control conditions: left or right) alternated every trial.

Blocks were of variable length, typically 6-20 trials (excluding those rejected). Subjective duration estimates (equivalent to subjective seconds in previous experiments) were obtained by taking the average of the four MOBS termination values in each condition. In the saccade conditions, each estimate was corrected post hoc to match the time the first circle was on screen following target foveation by subtracting the average time the eye was in motion following the triggered change to a circle (averaged across all four blocks). The experiment took around ninety minutes to complete.
Statistical analyses. In addition to subjective duration estimates, a measure of timing variability was obtained by calculating for each subject the standard deviation across the four MOBS-derived values. Standard parametric tests (repeated measures ANOVAs and MANOVAs, bonferroni-corrected t-tests and linear regressions) were used to assess differences across conditions with alpha set at 0.05 and appropriate corrections made for sphericity violations (as per Experiment 1d).

In assessing the possible role of non-specific arousal on the pacemaker, data was also fitted to a simple model. It is possible to envisage arousal undergoing a rapid rise during eye movement and speeding the pacemaker, then falling back to baseline with some timecourse. In this case, the clock might be accelerated for both the post-saccadic stimulus and the comparison stimulus, with a larger effect for the post-saccadic stimulus yielding a relative subjective lengthening of this percept (i.e. chronstasis). In the model employed here, arousal was assumed to decay exponentially back to a baseline level following the point at which the eyes first fixated the post-saccadic stimulus according to the function:

\[ y = sa^t + 1.0 \]  

where \( s \) is a scaling parameter, \( a \) is a decay rate parameter, \( t \) represents time since saccade termination in seconds, and \( y \) is arousal level (equivalent to clock rate) as a proportion of baseline. For any post-saccadic period between \( t_1 \) and \( t_2 \) subjective time will equal:

\[ s \left( \frac{a^t}{\ln a} + t \right) \]

Equation (2) was employed with an iterative least-squares fitting procedure (programmed in house). Values of \( s \) and \( a \) were derived that minimised the squared difference between predicted subjective time for the
comparison stimulus and that predicted for a post-saccadic stimulus (equal to the comparison stimulus minus the empirically determined mean effect size) simultaneously for all four saccadic conditions. The search regions were 0.001 to 0.500 for $a$, 0.01 to 1.00 for $s$ (i.e., any steep exponentially decaying curve for which the pacemaker had not been raised to more than 200% of baseline). A second iterative least-squares procedure determined the model's predictions for effect size in each condition based on the best fitting parameters $a$ and $s$.

Results and discussion.

Saccade characteristics. For the four levels of stimulus duration, saccades took an average of 56.6, 54.9, 55.4 and 54.2 ms respectively.

Time estimates. Figure 6.1 shows subjective duration estimates in all eight conditions. Chronostasis is clearly evident at all four levels of stimulus duration, with saccade conditions yielding reduced subjective duration estimates. A two-factor ANOVA supported this conclusion, showing a main effect of eye status ($F = 7.741$, df = 1, 9, $p = .021$). The main effect of stimulus duration ($F = 192.378$, corrected df = 2, 17, $p < 0.001$) represented a predictable linear trend from shortest to longest stimulus duration across both levels of eye status (trend test, $F = 284.13$, df = 1, 9, $p < 0.001$). There was no significant interaction between eye status and stimulus duration suggesting a constant effect size across comparison stimulus duration. Visual inspection, however, suggested that there might be some small multiplicative component (compare the 86 ms effect at 333 ms with the 167 ms effect at 1333 ms). To assess this possibility, each subject's MOBS-derived subjective duration estimates (one per block, hence four per level of eye status) were fitted using linear regression. All fits were significant at $p = 0.05$, yielding a slope and intercept value for each subject. Across subjects, mean slopes were 1.075 and 0.999, while mean intercepts were -72.3 and -136.6, for constant fixation and saccade conditions respectively. Hence both
multiplicative (slope) and constant (intercept) effects were evident as trends, although neither reached significance in a t-test. Both dependent variables were entered into a MANOVA, which indicated that an optimal linear combination of the two narrowly missed significance \((p = 0.0628)\). Normalised to reflect absolute differences between the two variables, this optimal value equalled \((\text{slope} \times 1.70) + (\text{intercept} \times 1.85)\). Hence both variables contributed a similar amount towards the overall difference between saccade and control conditions.

In the introduction, a strong multiplicative account was contrasted with a prediction of constant effect size across stimulus duration. The ANOVA appears to provide support for the latter explanation, but this interpretation relies upon a negative result (a failure to obtain an interaction). Stronger support would have come from a significant

![Graph showing mean time matched to a variable length comparison stimuli in saccade and constant fixation conditions for four levels of comparison stimulus duration. Error bars show standard deviations.](Image)

**Figure 6.1.** Mean time matched to a variable length comparison stimuli in saccade and constant fixation conditions for four levels of comparison stimulus duration. Error bars show standard deviations.
difference between the control and saccade intercepts from the regression analysis, but this failed to emerge in a t-test. A significant difference in slopes would have supported the multiplicative account, but again this failed to emerge when this variable was tested in isolation. Power analyses showed that detecting these differences would have required a much larger sample. Predicted differences in slope (.11) and intercept (110 ms) required $n = 42$ and $n = 18$ respectively to achieve a power of 0.8 at $\alpha = 0.05$. Detecting a mixed pattern would have required an even greater number of subjects. Consequently, conclusions must remain tentative. However, based on the results of the MANOVA, which narrowly missed significance when the two variables were combined, it appears that both constant and multiplicative effects may have been evident. The degree of multiplicative scaling is clearly less than that required to completely explain chronostasis; for this to be the case, the effect size should have been four times as great in the 1333 ms condition as in the 333 ms condition. Hence, the working hypothesis proposed so far (that the post-saccadic stimulus is predated to a point prior to saccade initiation) should perhaps be supplemented with a less specific component of the effect that scales with stimulus duration. This interpretation will be returned to shortly in the context of the internal clock model.

Interestingly, although the chronostasis effect is numerically larger with increasing stimulus duration, it is less reliable ($t = 3.79$ for control/saccade contrast at 333 ms, $t = 1.87$ at 1333 ms) reflecting greater underlying variability. Mean standard deviations for subjective duration estimates are shown in table 6.2. They grew proportionally with stimulus duration in an approximately linear manner. This is not surprising, comprising another demonstration of the ubiquitous finding of scalar variability for duration judgements (Allan, 1979). Statistical support emerged from a two-way ANOVA, showing a main effect of stimulus duration ($f = 14.001$, corrected $\text{df} = 1, 12$, $p = 0.001$) and subordinate linear trend ($f = 22.615$, $\text{df} = 1, 9$, $p = 0.001$). Mean standard deviations did not differ between control and saccade conditions however, with no significant
interaction. This result contrasts with those obtained in Chapter 3 using the standard paradigm (greater variability in saccade conditions). However, these differences were not always reliable, and there is a trend towards increasing variability for saccade conditions at 667 and 1000 ms stimulus durations in the current data.

<table>
<thead>
<tr>
<th>Eye status</th>
<th>Stimulus duration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>333 ms</td>
</tr>
<tr>
<td>Control</td>
<td>55</td>
</tr>
<tr>
<td>Saccade</td>
<td>57</td>
</tr>
</tbody>
</table>

Table 6.2. Mean standard deviations across four MOBS derived subjective duration estimates, shown for control and saccade conditions at four levels of stimulus duration.

With regard to the internal clock model, a number of components might be responsible for the substantial constant contribution to chronostasis obtained here across stimulus durations (refer to Figure 1.1 for details). The switch must be closed to initiate a period of pulse accumulation, so perhaps the simplest mapping of the predating hypothesis onto the clock model is to suggest that the switch is closed early on, prior to movement initiation. An alternative account might posit that a quantity of pulses that is related to movement duration is dumped into the accumulator at some point shortly after movement termination, giving the impression of a prolonged duration. These two accounts might be married if we were to assume one clock that ran for the duration of the movement, the contents of its accumulator being added to that of a second clock (measuring stimulus duration) when appropriate conditions were met.

Another potential locus for a constant effect is the comparator. Rather than relying on a simple decision rule such as: 

\[
\text{if duration (stimulus)} > \text{duration (comparison stimulus) then respond "greater"}
\]

it is easy to conceive of a situation in which this criterion is altered by a constant amount.\(^1\) Here the conscious sensation of duration is assumed to arise only

\(^1\) Decision rules are a subject of some debate within the prospective timing literature, particularly in the context of scalar expectancy theory (see Allan, 1998). They are,
following such a decision process, with no direct access to the (veridical) underlying representation.

The comparator, however, is a highly flexible component, so could just as easily produce a multiplicative effect with an alternative alteration of the decision rule. Similarly, it is easy to imagine a multiplicative transformation being applied to the pulse count during its transferral between memory stores (e.g. the accumulator and short term memory).

![Diagram](image)

**Figure 6.2.** Schematic for a transient arousal-based account of saccadic chronostasis. Pacemaker speed ramps during movement, then decays back to baseline following the function \( y = s a^t + 1.0 \) (see Methods for an explanation of terms). Perceived duration is found by integrating the area under the curve, and varies depending upon time relative to saccade termination. The curves shown here represent the best fitting model, where \( a = 0.04 \) and \( s = 0.51 \), for the two most extreme stimulus duration conditions. Dotted lines outline the period for which the post-saccadic stimulus must be displayed to equal the comparison stimulus (solid lines) in perceived duration.

Perhaps the most intuitively plausible accounts of any multiplicative component of chronostasis, however, relate to attention or arousal (note that given that this component has not yet been demonstrated statistically, the null hypothesis that no such component actually exists should be added to these alternative accounts). Arousal is generally assumed to increase pacemaker speed, and would therefore yield a multiplicative effect. However, this effect would have to be tied to the post-saccadic stimulus in some manner to be relevant to the current experiment. Arousal is generally

---

however, specific to the timing paradigm being employed, and have not been extensively considered for comparison methodologies such as that employed here.
considered to be fairly non-specific, affecting many processes for a given period of time. Any transient state of arousal capable of influencing duration estimates for the 1333 ms duration stimulus should therefore affect both the post-saccadic and *comparison* stimuli in the 333 ms condition (given that the interval between them is only 500 ms) yielding no overall effect. However, this analysis assumes that any arousal increase operates as a step function; the observer is more aroused following an eye movement, then they return immediately to baseline. If we instead consider an arousal function that rises steeply then decays slowly, it is possible to conceive predictions that conform roughly to those obtained here. Figure 6.2 demonstrates this possibility schematically using a function that decays exponentially (see figure legend and methods). It provides a reasonably accurate fit to the current data, yielding expected effect sizes of 79, 126, 146 and 153 ms for the four stimulus conditions (compare these to the actual effect sizes of 86, 122, 132 and 167 ms respectively). However, this fit is not significantly better than simply relying on the mean given the limited number of data points ($f = 6.3$, $df = 1, 2$, $p > 0.05$). This contrasts with a simple straight-line equation fitted by performing a linear regression on effect sizes ($y = 0.07577 t + 63$, $f = 53.15$, $df = 1, 2$, $p = 0.018$). It should also be noted that the model is not quite true to the data, as it effectively assumes veridical control performance with chronostasis having its effect relative to this baseline. In fact, any multiplicative component of chronostasis in the current data arose because control estimates rose with a slope above unity, not because saccade estimates demonstrated a slope below unity. The arousal model could easily be tested further by manipulating the interval between the test and comparison stimuli.

Returning to an explanation in terms of one constant and one multiplicative component, attention provides another example of a multiplicative effect. There is some debate regarding the usefulness of adding a separate "attentional gate" component to existing clock models, operating to scale the number of pulses passing from the pacemaker to the accumulator (Lejeune, 1998; Zakay, 2000). An alternative account suggests
that the switch is simply closed and opened in rapid succession as attention is switched to and from the timing task. Both accounts, however, share a multiplicative prediction for increasing perceived duration with increasing attention to a prospective temporal judgement task. Unlike arousal, attention might well be selectively increased for the post-saccadic stimulus. The reasons for any such increase, however, remain unclear.

Two firm conclusions which can be drawn from Experiment 5a are that chronostasis emerges even for brief post-saccadic stimuli (as brief as 220 ms, the mean duration of stimuli matched to a 333 ms comparison stimulus) and does not depend upon a sequence of post-saccadic stimuli akin to a second hand. The former result suggests that if there are any assumptions that must be met regarding the temporal perseverance of the post-saccadic stimulus for the brain to instigate chronostasis, they apply only for extremely brief stimulus presentations. When the offset of a very brief stimulus is judged relative to the onset of a reference stimulus (a variant of the temporal order judgement paradigm) discrepancies emerge for high intensity stimuli less than 130 ms in length (Efron, 1970a; Efron, 1970b). The pattern of errors is systematic, indicating that subjects effectively perceive stimuli below 130 ms in length to persist for 130 ms, a kind of minimal perceptual duration. The shortest duration tested here is not much longer than this, suggesting that chronostasis would probably be obtained right down to this minimum value, although how the two effects might interact is not clear.

Demonstrating chronostasis in the absence of an ongoing sequence of stimuli rules out explanations in terms of a particular ongoing post-saccadic context and supports the notion that the first post-saccadic percept is being manipulated in some way. It also weakens any analogy with the effect obtained for trains of visual stimuli under static viewing conditions, which presumably depends upon such an ongoing context (Rose and Summers, 1995). Changes to another repeatedly employed aspect of the standard chronostasis paradigm, the voluntary nature of the saccade, will be considered next.
Experiments 5b and 5c

In the experiments reported thus far, chronostasis has been elicited using a voluntary saccade. Although it is reasonable to argue that the highly repetitive nature of the experimental task yields a stereotyped response that is somewhat removed from a freely elicited action, the saccades studied nonetheless depend on internally-mediated decision processes. At the psychological level, volition may have an important influence upon whether or not chronostasis is obtained. At an anatomical level, movements that arise in volitional as opposed to externally cued contexts employ different brain regions, so contrasting chronostasis effects might provide clues for anatomical localisation. Both considerations can be addressed by varying the type of saccade that is employed in a visual chronostasis paradigm and will be dealt with in turn.

Chronostasis is not the only temporal illusion that has recently been reported in the context of movement. Haggard, Clark, and Kalogeras (2002) made use of the Libet clock paradigm to investigate the relationship between the perceived time of various combinations of movements and briefly presented auditory stimuli. Subjects observed the rotating hand of an on-screen clock and estimated its position at the point they heard a tone, pressed a key, or were caused to produce a hand movement involuntarily via the application of trans-cranial magnetic stimulation (TMS) over the contralateral motor cortex. In a subset of conditions, both a keypress (or TMS-induced movement) and a tone were presented such that the tone was clearly contingent upon the movement (following it by 250 ms). Relative effects were calculated in the movement-plus-tone conditions by adjusting subjects' estimates according to the offset values obtained in the single event conditions. This provided an estimate of any shift in the judged position of an event dependent on the presentation of the second event (and neatly side-stepped objections regarding modality and attention-related biases). Interestingly, presenting a tone with a movement caused the
perceived times of occurrence for both events to be drawn closer together, as if they had been temporally bound. This finding shows a striking resemblance to chronostasis, where a post-movement event is extended towards the point of movement initiation, although the stimuli used (brief rather than continuous) and the timecourses of the effects differ. A second result was that this binding effect disappeared (and was even reversed) when the tone was presented with a TMS induced movement. This lead the authors to term their effect “intentional binding,” considering it to depend upon the volitional nature of the motor act.

In the light of these experiments, it seems natural to ask whether chronostasis also depends upon volition. Varying the freely timed/cued nature of a saccade is not as strong a manipulation as inducing a movement with TMS (even peripherally cued saccades provoke an “I did that” sensation, in contrast to the subjective oddity of an electrophysiologically induced movement). Nonetheless, we might reasonably predict that chronostasis might be modulated for cued saccades.

The issue of anatomical localisation is clearly related to these considerations. If we return briefly to a consideration of timing processes such as that employed in Experiment 5a, it is apparent that information about some aspect of the saccadic motor act must be being transmitted to the relevant clock component/s in order to obtain the observed modulation of perceived time. We can therefore consider where in the motor system such a signal arises. The oculo-motor plant receives its primary input from the brainstem burst generators of the reticular formation. Different types of saccade selectively recruit higher cortical areas during saccade generation (Scudder, Kaneko, and Fuchs, 2002). So far, chronostasis has only been demonstrated for voluntary saccades. If an effect of similar magnitude arises for other saccades, then the information used to adjust perceptual experience must arise in areas common to both types of saccade. Hence while even express saccades require early visual areas, the superior colliculus and the brainstem (Hopp and Fuchs, 2002) other kinds of saccade also employ areas in frontal and parietal cortex which may act as the source of any signal.
Experiment 5b was a pilot study intended to initially assess whether chronostasis might emerge for saccades made in reaction to a stimulus change at fixation. In Experiment 5c the comparison was extended to saccades cued by a sudden peripheral onset at one of two positions, a condition considered to be more representative of real-world stimulus-driven saccades and less volitional in nature. In addition, anti-saccades (saccades made in a direction opposite to a sudden peripheral onset) were considered. This task requires active suppression of a dominant response, yielding a high volitional component and slow reaction times. It was added to test the specific hypothesis that the signal initiating chronostasis might act as a pre-motor time marker to which the post-saccadic stimulus is predated. If we further assume that such a signal were to arise early in motor preparation (i.e. before the processes that produce a reaction time deficit for anti-saccades, such as the re-specification of saccade direction) an effect on chronostasis is anticipated. Specifically, effect size should be enhanced in this condition by an amount roughly commensurate with the observed increase in reaction time.

**Experiment 5b**

**Methods.**

**Participants.** 12 subjects (10 male, mean age 30.6, SD 5.3) completed Experiment 5b. 2 had previously participated in experiment 5a.

**Apparatus.** Apparatus was identical to that employed in Experiment 5a with the following exceptions. Eye to screen distance was 65 cm. Stimuli consisted of a cross and/or a digital counter, initially set to “0” and counting through the digits “1” to “4”, and subtended approximately 0.5° of visual angle.
**Design.** A repeated-measures design was employed with three conditions. The first voluntary condition involved a voluntary saccade of 20°. The second cued condition involved an identical saccade made in reaction to a stimulus change at fixation. The final control condition involved constant fixation at matched eccentricity (±10°). Trials from each condition were presented in separate blocks, with four blocks per condition. A single block was completed from each condition in turn, with order counterbalanced across subjects.

**Procedure.** In the voluntary conditions, subjects fixated a cross on one side of the screen, initiated the trial with a mouse key press then made a voluntary saccade to a target “0” on the other side. In the cued conditions, they were required to maintain fixation on the initial cross until it changed colour to become red, at which point they made a speeded saccade. The change to red occurred randomly within the region 500-1500 ms after trial initiation. Eye movement triggered a change of digit to a “1” when the saccade had travelled one fifth of the distance to target. The “1” remained on screen for 400-1600 ms; 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. Saccade start/end points were calculated automatically and trials rejected as per Experiment 5a. In control (constant fixation) trials, subjects simply fixated a “0” at equivalent eccentricity that changed to become the judged digit (“1”) 500 ms after the subject’s mouse key press. Direction of saccade (saccade conditions: left to right and vice versa) or position of the counter (control conditions: left or right) alternated every trial.

In all conditions, the computer controlled the duration of the first digit by a modified binary search (MOBS) procedure (low boundary 400 ms, high boundary 1600 ms, initial presentation random 800-1200 ms, five reversals to terminate). Blocks were of variable length, typically 6-20 trials excluding those rejected. In the saccade conditions, each estimate was
corrected post hoc to match the time the “1” was on screen as per Experiment 5a. by subtracting the average time the eye was in motion following the triggered change of digit (averaged across all four blocks). The experiment took around forty minutes to complete.

**Statistical analysis.** Standard parametric statistics were employed as per Experiment 5a.

**Results and discussion.**

**Saccade characteristics.** Saccades took an average of 66.3 ms in the voluntary condition and 67.6 ms in the reactive condition. Average reaction time in the reactive condition was 362 ms.

![Graph showing subject duration estimates for conditions involving a voluntary or reactive saccade of 20° extent or constant fixation. Error bars show standard deviations.](image)

**Figure 6.3.** Mean duration estimates for conditions involving a voluntary or reactive saccade of 20° extent or constant fixation. Error bars show standard deviations.

*Time estimates.* Figure 6.3 shows mean subjective second estimates in all three experimental conditions. Judgements were quite accurate in the control condition, with lower subjective second estimates in the voluntary and cued saccade conditions. It is apparent, however, that the size of the effect in the voluntary condition is rather smaller than that typically obtained in chronostasis experiments. An ANOVA testing differences across all three conditions narrowly failed to reach significance ($f = 2.932$, df = 2, 22, $p = 0.074$). Because of the failure to obtain overall significance, follow ups employed a Bonferroni correction in place of Fisher’s LSD. Only the difference between control and cued conditions approached significance ($p = 0.065$).
The failure to replicate the standard chronostasis effect is surprising, but probably simply represents a type II error like that found in Experiment 3a. Power was only 0.67 to detect a predicted 110 ms difference between control and voluntary conditions (planned comparison, $\alpha = 0.05$) yielding a substantial $\beta$ value of 0.33. This condition directly replicates the standard saccade conditions used in Chapters 2 and 3, so few other explanations are available. Although only marginally significant, the difference between control and cued conditions suggests that chronostasis can occur for saccades made in reaction to a central go cue. Given statistical vagaries, more thorough discussion will be postponed until results are reported for Experiment 5c.

Experiment 5c

Methods.

Participants. 26 subjects (15 male, mean age 30.5, SD 7.8) completed Experiment 5c. 1 had previously participated in experiment 5a.

Apparatus. Apparatus was identical to that employed in Experiment 5a with the following exceptions. Open circles were used as post-saccadic and comparison stimuli, but the latter were made red to aid clarity of judgements. Fixation crosses and circles subtended 1.1° of visual angle. Additionally, open squares were employed as peripheral targets, subtending 3.3°.

Design. A repeated-measures design was employed with three conditions. The first pro-saccade condition involved a reactive saccade of 20° to a peripheral target. The second anti-saccade condition involved an identical saccade made in a direction opposite to a peripheral target. The final control condition involved constant fixation at matched eccentricity (±20°). Trials from each condition were presented in separate blocks, with six blocks per
condition. A single block was completed from each condition in turn, with
order counterbalanced across subjects for the first 24 subjects. The final two
subjects were investigators, and completed the 18 blocks (in addition to a
further 12 blocks from two extra conditions not reported here) in a random
order.

Procedure. For saccade blocks of both kinds, black crosses were initially
displayed 20° to the left and right of a central red cross. In pro-saccade
blocks, subjects fixated the red cross and initiated the trial with a mouse key
press. 500 ms later a black outline box appeared around one or other
peripheral cross, directing the subject to make a speeded saccade in that
direction. The box appeared randomly to the left or right on each trial. In
anti-saccade blocks, the same sequence of stimuli was used, but subjects
were required to saccade to the cross around which the box had failed to
appear (i.e. in a direction opposite to it). Eye movement triggered the black
cross to be replaced with a circle when the saccade had travelled one fifth of
the distance to target. The circle remained on screen for 400-1600 ms. It
then disappeared, to be replaced by a red circle (the comparison stimulus)
after 500 ms. The comparison stimulus remained on screen for 1000 ms.
Subjects indicated whether the time they saw the first circle was longer or
shorter than that for which the comparison circle was displayed. The
duration of the first circle was controlled by a MOBS procedure (low
boundary 400 ms, high boundary 1600 ms, initial presentation random 600-
1400 ms, five reversals to terminate). Blocks finished when the MOBS had
terminated.

Saccade start/end points were calculated and trials rejected as per
Experiment 5a (note that this led to trials in which subjects initially moved
their eyes in the wrong direction being rejected). In control (constant
fixation) trials, subjects initially fixated a peripheral cross at equivalent
eccentricity. It was blanked 400ms after the subject’s mouse key press, then
replaced after a further 100 ms by the to-be-judged circle, with subsequent
stimulus presentation and subject responses as per saccade trials. Position of this fixation cross alternated every trial.

Blocks were of variable length, typically 6-20 trials (excluding those rejected). Subjective second estimates were obtained by taking the average of the six MOBS termination values in each condition. In the saccade conditions, each estimate was corrected post hoc to match the time the first circle was on screen following target foveation by subtracting the average time the eye was in motion following the triggered change to a circle (averaged across all six blocks). The experiment took around one hour to complete.

Statistical analysis. Standard parametric statistics were employed as per Experiment 5a.

Results and discussion.

Saccade characteristics. Saccades took an average of 58.4 ms in the prosaccade condition and 61.2 ms in the anti-saccade condition. Eye movements were recorded over a fairly large range in Experiment 5c (-20° to +20°) but an infra-red eye tracker was employed rather than EOG. This resulted in some nonlinearity at the extremes, but such an effect would not be expected to bias the procedure and average times are similar to those reported for saccades of this size in previous experiments (compare Experiments 5a and 5b).

Time estimates. Figure 6.4 shows mean corrected time estimates in all three conditions. In contrast to previous trends the control estimate for this subject group is rather high, but does not differ significantly from one second and will not be considered further. More importantly, estimates are substantially reduced in the pro- and anti-saccade conditions, which yield identical effect sizes of 90 ms relative to control. An ANOVA yielded a significant difference across conditions \( f = 5.448, \text{df} = 2, 50, p = 0.007 \) with pairwise
follow ups showing significant differences between control and pro-saccade (p = 0.007) and control and anti-saccade (p = 0.015) conditions but no differences between pro- and anti-saccades.

Chronostasis is clearly present for peripherally cued saccades of both types tested here. While such exact agreement between the pro- and anti-saccade conditions is rather fortuitous, it is apparent that the hypothesis that chronostasis would increase in the anti-saccade condition is not supported.

Mean reaction times were 274 ms in the pro-saccade condition and 335 ms for anti-saccades, a highly significant difference of 61 ms (t = 6.52, df = 25, p < 0.001) that conforms well with previous studies using pro/anti-saccade tasks (Cherkasova, Manoach, Intriligator, and Barton, 2002).² If chronostasis involved the backwards extension of the post-saccadic percept to a pre-motor event occurring prior to the (re)specification of saccade parameters required in the anti-saccade condition, an increase in effect size of similar magnitude would be expected. Although it did not emerge, a negative result in this case does not provide strong evidence against the hypothesis either, as power was only 0.56 to detect a 61 ms difference between pro- and anti-saccade conditions (planned comparison, α = 0.05).

Taken together, Experiments 5b and 5c strongly suggest that chronostasis does not occur only for volitional, freely-willed saccades. It

² Because trials could be rejected for a number of technical reasons in addition to an incorrect direction of response, no error analysis is presented here. However, informal observation of subjects’ performances suggested that incorrect responses arose much more frequently in the anti-saccade condition, arguing against a speed-accuracy trade-off account of the reaction time data.
arises when saccades are cued based upon an unnatural stimulus-response translation (Experiment 5b) and when they are elicited in a more natural manner by a sudden peripheral onset (Experiment 5c). Although the experimental context means that both of these conditions contain a higher order component of volition (a task set or response strategy has been chosen and movements are clearly being "made" rather than being purely reflexive) chronostasis does arise without a clear internal decision about when and where to move one's eyes. The failure to obtain an increased effect in the anti-saccade condition relative to the pro-saccade condition should not be over-interpreted, but some discussion seems warranted. It suggests that the differences between the two conditions that give rise to a substantial reaction time deficit for anti-saccades may occur prior to any signal used to modify the extent of chronostasis (e.g. that yielding the saccade-size dependency shown in Experiment 1a). The exact nature of the task differences are arguable, but it seems likely that they involve the suppression of a dominant response and the mapping of a stimulus onto an alternative response, processes that probably rely on attention-demanding central mechanisms. Hence not only is chronostasis a relatively low-level phenomenon (arising for relatively instinctive eye movements) but the time marking signal employed to modulate its effect size probably arises from some process downstream of any conscious intervention. In terms of the internal clock model, we can consider two alternative accounts of the constant component of chronostasis. Firstly, the switch of the relevant clock (or of an alternative clock operating purely to time the movement itself) might be opened at a given moment prior to movement initiation. These data suggest that that moment is rather late, perhaps reflecting the efferent motor command itself. Secondly, the information in the accumulator or short-term memory store might be being altered after the movement. In this case, afferent information about movement extent might be being employed to determine the appropriate adjustments. These accounts are purely speculative, far from exhaustive, and cannot be assessed based on the current data, but do suggest lines of future enquiry.
Turning to the issue of anatomical localisation, it was suggested earlier that the types of saccade capable of giving rise to chronostasis can offer insights into the regions from which any motor-related command to initiate the process must arise. Experiment 5c demonstrated chronostasis for saccades made in response to the onset of peripheral stimuli. Because this kind of saccade is the most low level studied thus far, it effectively limits the regions from which a relevant motor command might arise (more complex types of saccades make use of higher cortical areas, but all must rely on areas projecting more directly to the brainstem burst generator). Hence areas believed to play a role in more cognitive saccades but which are not typically involved in low-level saccades can be eliminated from consideration. Single pulse transcranial magnetic stimulation of the posterior parietal cortex, for example, has been shown to effect the onset time and metrics of memory guided saccades (Muri, Gaymard, Rivaud, Vermersch, Hess, and Pierrot-Deseilligny, 2000) but this region may play little role in reflexive saccades (although see Gaymard and Pierrot-Deseilligny, 1999, for an alternative view). It must be emphasised that this discussion relates to the origin of any signal to initiate chronostasis, not the region to which that signal is sent and in which it might be employed. It was noted in Chapter 3 that the nature and timecourse of chronostasis suggests a possible link with the pre-saccadic shifts of receptive fields demonstrated for neurones in the lateral intraparietal area of monkeys (Duhamel, Colby, and Goldberg, 1992). In fact, such remapping is evident in other regions including the superior colliculus, frontal eye fields and early visual cortical areas (Ross, Morrone, Goldberg, and Burr, 2001; Umeno and Goldberg, 1997). Excluding regions like posterior parietal cortex as the origin of the signal initiating chronostasis does not imply that they do not receive and act upon such a signal.

Even having rejected certain higher cortical loci, a great number of regions still remain to be considered, being active for all the saccade types employed here. Afferent information from the plant itself has already been mentioned, and the brainstem burst generator is clearly a candidate as the
final source of efferent information. The superior colliculus is widely regarded to be the primary interface with the burst generator (e.g. Scudder, Kaneko, and Fuchs, 2002; Moschovakis, Scudder, and Highstein, 1996) although lesions do not completely prevent saccades occurring via other routes. This region has recently been shown to send corollary discharge signals upstream to the frontal eye fields. Monkeys performing a double saccade task failed to fully correct for the displacement caused by the first saccade when this pathway was blocked (Sommer and Wurtz, 2002). Might such a pathway also convey information used in chronostasis?

These possibilities cannot be excluded based on manipulations of saccade type alone. Other areas remain viable in light of the current data, but might reasonably be excluded in future by using an even lower-latency reactive saccade such as the express saccade. For example, the frontal eye fields project to the superior colliculus and have weak but direct projections to the brainstem burst generator. They also show retinotopic mapping like that in the superior colliculus and consistent with an important role in determining the spatial metrics of saccades (Thompson and Bichot, 1999). These areas may seem viable then, although some authors have suggested that they are relevant for voluntary rather than reflexive saccades (Schneider and Deubel, 2002). However, they appear to have no role when express saccades are generated via the gap paradigm (Hopp and Fuchs, 2002). The prefrontal cortex, too, might be excluded using this approach, as transcranial magnetic stimulation over this area increases the likelihood of express saccades, suggesting that it typically inhibits these responses and does not play a role when they occur spontaneously (Muri, Rivaud, Gaymard, Ploner, Vermersch, Hess, and Pierrot-Deseilligny, 1999). At present, all these areas remain viable sources of the signal to implement chronostasis. What is clear, however, is that this signal arises rather later than a strongly volitional account of chronostasis would predict.

General discussion
In Experiment 5a, comparison stimuli were altered relative to previous studies, with a single reference used in preference to a train of stimuli. Additionally, the duration of the comparison stimulus was varied in the region 333-1333 ms. Saccadic chronostasis emerged in all conditions, clearly demonstrating the utility of the single comparison stimulus approach and showing that the illusion does not depend upon an ongoing context of discrete changes. Additionally, the illusion does not appear to require some minimum post-saccadic exposure period to emerge (unless it is extremely brief). The data fell somewhere between an effect that is entirely constant across comparison stimulus durations and one that scales multiplicatively with them. Although statistical power was insufficient to convincingly discriminate between these alternatives, the most plausible scenario appears to be one in which a constant component of chronostasis, like that hypothesised so far to account for the illusion's dependence upon saccade extent, is supplemented by a further multiplicative component. It is interesting to note that the constant component found in Experiment 5a (the difference in mean intercept values derived from individual subjects' regressions) was almost identical to the mean saccade duration for this experiment (64 and 55 ms respectively). The multiplicative component may or may not be tightly linked to the post-saccadic stimulus for its entire duration. These data allow the initial development of hypotheses regarding the way the illusion operates within the context of the internal clock model, but further experiments are required to delineate these alternative accounts.

In Experiments 5b and 5c the standard voluntary saccadic condition was expanded to test cued saccades of various types. Experiment 5c also provided further evidence of the validity of a procedure employing only a single comparison stimulus. Saccadic chronostasis emerged for all the saccade types tested here, suggesting that it does not depend upon an internal decision to produce a saccade. Saccadic chronostasis appears to be a prime example of a motor act interacting with sensory systems to alter the overall perceptual experience. The signal used to achieve this modification of perception must arise rather late in the chain linking decisions to motor
actions, perhaps at the level of the efferent command itself. Anatomically, the most likely regions for the generation of this signal appear to be the superior colliculus and brainstem, although higher cortical areas cannot be excluded.

Taken together, these studies point to the generality of the phenomenon of saccadic chronostasis. The original idea that the post-saccadic percept is effectively being stretched backwards towards a point preceding saccade initiation is broadly supported. This process appears to be operating regardless of the duration of the post-saccadic stimulus or the kind of saccade that is being made, suggesting that the illusion is ubiquitous in our everyday experience and may well be filling in the experiential gaps left by saccadic suppression. In the next chapter the generality issue will be further addressed, extending chronostasis beyond the saccade to investigate its existence for reaching movements of the arm.
Chapter 7. Manual chronostasis

The experiments presented in Chapter 2 were motivated by the initial observation of the stopped clock illusion, which naturally lead to a methodology in which saccades played a central part. However, an intuitively similar everyday experience, the dead phone illusion, occurs in the context of arm rather than eye movements. Sometimes we may become distracted while making a phone call, for example when we are confronted with a repetitive “engaged” tone and report this to a friend. Upon returning the phone to our ear, we may gain the distinct impression that it has gone dead (the period of silence is too long) before the next tone finally arrives and the normal repetitive pattern resumes. This extension of an auditory silent period following an arm movement certainly seems analogous to the extension of a post-saccadic visual percept found in saccadic chronostasis and suggests that the illusion may be more general than the current saccadic explanation would suggest.

While the experiments reported here were being completed, relevant data was also being collected in two other labs. Newport, Osborne, Wakely, Walsh, and Jackson (2002) investigated a patient with congenital ophthalmoplegia who had never made saccadic eye movements, instead making rapid movements of her entire head between fixations. They reported that she showed no chronostasis in a replication of the original paradigm where counter change was triggered by her head movements. In a second unrelated paper, Hodinott-Hill, Thilo, Cowey, and Walsh (2002) investigated the dead phone illusion, reasoning that it might arise from a shift of auditory attention rather than an arm movement. They employed a rather different method to investigate the illusion. A series of tones separated by one second was presented to one ear. The fourth tone was either higher or lower than proceeding tones, and subjects responded by pressing one of two keys. This keypress initiated an empty period of variable length prior to the resumption of the tone pattern. The tones could resume in the same ear or in the other ear, presumably preceded by a shift of
spatial attention in the latter case. The first interval after the keypress was
judged relative to those that followed and adjusted using a MOBS procedure
like that employed throughout this thesis. Subjective seconds were found to
be significantly lower when the judged interval contained a shift of spatial
attention. These two experiments appear to suggest that chronostasis might
not arise for arm movements (based on the former study) or is in fact the
result of attention shifts (based on the latter). A detailed consideration of
methodological differences and alternative conclusions will be postponed
until the General discussion and Chapter 8.

The first two experiments reported here examine the context in
which any reach-dependent chronostasis might arise. In the experiments
reported in previous chapters, saccadic chronostasis was demonstrated for
the post-saccadic visual stimulus, that aspect of the world that is naturally
revealed or enhanced by movements of the eye. The most analogous
sensation for reaching movements is the newly revealed tactile information
that they yield. Saccadic chronostasis also appears to vary with eye
movement parameters (Experiment 1a). For these reasons, Experiment 6a
searched for evidence of chronostasis using reaching movements of varying
extents to a vibrating stimulus. In addition to short and long reach
conditions, expected to give rise to effects dependent upon their movement
durations, a double reach condition was added to investigate whether the
resultant magnitude of any chronostasis effect would reflect the final short
reach component or the whole double movement.

**Experiment 6a**

*Methods.*

*Participants.* Of the 30 participants who completed Experiment 6a, six were
rejected because their data did not permit a valid subjective second estimate
to be calculated in all conditions (see below). The final sample comprised
24 subjects (15 male, mean age = 30.6, SD = 6.9).
Apparatus. Subjects sat before a 22" CRT colour monitor refreshing at 60 Hz. Head position was stabilised using an adjustable chin rest (approximate eye to screen distance of 40 cm). Fixation was monitored by recording from the left eye using an infra-red eye tracker (Microguide 1000 spectacles, low-pass filtered at 40 Hz). Fixation point was set using a cross displayed in the centre of a small moveable rectangular window subtending approximately 5°. Movement initiation was recorded using a digital switch (built in-house) set upon a mobile base that was initially depressed then released. For the double step condition, an intermediate stopping point consisted of a strain gauge (F259 button load cell and calibrated load cell amplifier: Novatech Measurement Ltd) set upon a mobile base and receiving additional amplification (D150 amp: Digitimer). The tactile stimulus at the reach destination consisted of a second identical strain gauge set upon a vibrator (101 vibrator: Ling Dynamic Systems) powered by its own amplifier (PA25E: LDS). The vibrator was driven using a sine wave oscillating at 60 or 120 Hz. In both cases a single cycle consisted of 100 sampled points, output with varying rate. An accelerometer (Specialised Laboratory Equipment: tremor transducer) was attached to the subject’s right (reaching) index finger. Its signal was passed via an AC amplifier (D150 amp: Digitimer; band pass filtered 0.032-300 Hz). All signals were sampled at 200 Hz. Additional digital filtering was employed in some cases (see procedure below). The vibrator and other reach apparatus was set upon a desk isolated from a second desk upon which the chin rest was mounted; subjects were permitted to have direct body contact only with this latter desk. The experiments were controlled by a PC interfaced with a 12 bit A/D card (National Instruments DAQ 1200). A second PC was used to generate constant noise, delivered via headphones with an output of 80-85 dBA measured at the ear. This noise consisted of a combination of 60 Hz and 120 Hz pure tones, designed to mask that produced by the vibrator. The experimental set-up is shown in schematic form in Figure 7.1.
Figure 7.1. Schematic of experimental apparatus showing a trial from a double reach block. Subjects fixated the on-screen cross, then released a digital switch (obscured by hand in figure) and reached across to the target strain gauge, touching the intermediate strain gauge en route. In the long reach condition, the intermediate strain gauge was removed. In the short reach condition, it was replaced with the digital switch.

**Design.** A repeated-measures design was employed with four conditions. The first *short reach* condition involved a leftwards reaching movement of 15 cm. The second *long reach* condition involved a 50 cm reach made from a different more extreme start point to an identical termination point. In the third *double reach* condition the reach began 50 cm from the termination point, with a transient touch down 15 cm before the movement was completed. The final *control* condition involved resting the right (reaching) hand upon the termination point. Trials from each condition were presented in separate blocks, with six blocks per condition. A single block was completed from each condition in turn, with order counterbalanced across subjects.

**Procedure.** In conditions requiring an arm movement, subjects initially pressed down a digital switch set in a variable position to the right of the workspace. This position was 50 cm to the right of the vibrator in the long and double conditions and 15 cm to the right of the vibrator in the short condition. The vibrator itself was set ahead and approximately 7.5 cm to the
left of the subject’s midline, with the target strain gauge mounted upon it. This target strain gauge occupied a position in front of and near the bottom display edge of the monitor. On the monitor itself, a fixation window (with a central fixation cross) was moved to occupy a position just above and approximately 7.5 cm to the right of the target strain gauge. In the double condition, the second intermediate strain gauge (used to record subjects’ touch downs) was placed approximately 7.5 cm to the right and just below the fixation cross (level with and 15 cm across from the target strain gauge). Subjects typically had to look straight ahead and slightly downwards to fixate. In this position they could see the target strain gauge and, in the double condition, the intermediate strain gauge, but only in their peripheral vision. This fixation position was chosen to prevent subjects seeing the tiny movements of the target strain gauge when the vibrator was operating. In addition, subjects wore headphones playing masking noise to prevent any auditory cues about the state of the vibrator from reaching them.

Upon a verbal cue from the experimenter subjects made a rapid arm movement from the digital switch towards the target strain gauge. In the double condition, they were required to briefly make contact with the intermediate strain gauge en route. Their release of the digital switch initiated data acquisition for the trial and caused the vibrator to begin oscillating at 120 Hz. It continued to oscillate at this rate for a variable period (600-2000 ms) such that it was always in this state when subjects first touched it. Some time after this initial contact (after the remainder of the initial variable period) it changed to oscillate at 60 Hz for a period of exactly 1000 ms, before proceeding to alternate again between the two frequencies for periods of 1000 ms each (complete pattern: high-low-high-low). The latter three one-second intervals comprised the reference stimuli. The change from 120 to 60 Hz and vice versa was always reported to be quite distinctive based on finger contact. Subjects were required to judge whether the time they had felt the first interval was longer or shorter than that for which they experienced the later reference intervals. They reported this judgement to the experimenter, who entered it before readying the next
trial. A large window on screen presented the experimenter with a 1000 ms snapshot of signals recorded from the release of the digital switch. Signals from the accelerometer, eye tracker, and both strain gauges were displayed, as well as filtered versions of these signals and vertical lines representing the times the computer had assigned to key events such as strain gauge contact/release (see below). The experimenter could choose to reject trials at this point (e.g. if a saccade appeared in the eye trace or contact times looked incorrect).

The duration of the first 120 Hz oscillation period was controlled using a MOBS procedure (low boundary 600 ms, high boundary 2000 ms, initial presentation random 1100-1500 ms, five reversals to terminate). The range of values presented differed from previous experiments using eye movements because movement times were longer (the amount of time for which the subject’s finger actually contacted the target strain gauge being equal to presentation time minus movement time). The times at which the subject contacted the target strain gauge and contacted/lifted off from the intermediate strain gauge (double condition only) were calculated automatically. As a default setting, a second order 30 Hz low-pass Butterworth filter was applied to both strain gauge signals in both forward and reverse directions to prevent any phase shift. Filter coefficients were derived using commercial software and implemented by the experimental software as described in the supporting literature (Matlab: the Maths Works Inc.). The filtered data were then searched for a sudden rise (and fall in the case of the intermediate strain gauge) using a combined criterion: both the absolute value of the signal and its first derivative (sample n compared to sample n-3) had to exceed (or fall below) threshold values based on background signal noise (recorded in the time window 50-100 ms after movement initiation). These estimated contact/release times were displayed against both filtered and unfiltered traces and could be adjusted by the experimenter at this point. Filter order and low-pass values could also be altered trial by trial from within the following range: 10, 20, or 30 Hz high cut frequency; 2nd or 5th order. Trials were rejected automatically if contact
times could not be determined or if the subject's eye signal (sampled for 1000 ms after movement initiation and once at each subsequent change of vibrator oscillation frequency) moved outside boundaries set and updated periodically by the experimenter. Additionally, in the double condition, trials were rejected if the period for which the subject had contacted the intermediate strain gauge exceeded 300 ms.

Control blocks required no movement. Subjects simply rested their right hand on the target strain gauge, with the experimenter initiating an identical sequence of four periods of tactile stimulation that began 500 ms after a mouse key press. Subjects were encouraged to remove their headphones for the rest periods between blocks. Blocks were of variable length, typically 6-20 trials. Because movement times were quite variable across trials, MOBS termination values were not modified by average reach times to produce subjective second estimates. Instead, each trial was modified by subtracting its individual reach duration (zero in the control condition). The resultant contact times and judgements were entered into logistic regression analyses.

In order to ensure that subjects relied entirely upon tactile cues, an initial pre-test phase was completed to assess the availability of visual and auditory information. Subjects fixated and were played noise (mimicking standard experimental conditions) but had no contact with the target strain gauge or any equipment that had not been isolated from it. The experimenter initiated each trial, causing the small window containing the fixation cross to turn black for one second, then white for one second, before returning to its standard red colour. The vibrator oscillated at either 60 or 120 Hz during one or other of these intervals (never both). Subjects reported (guessed) which colour interval had contained vibration. Forty trials were presented in random order, comprising ten 60 Hz and ten 120 Hz presentations in both black and white intervals. Responses were classified correct or incorrect, with guessing expected to yield 50% correct performance in the absence of visual/auditory cues. Together, pre-test and experiment took around 90 minutes to complete.
Statistical analyses. Logistic regression was used to yield subjective second estimates (see Experiment 1a). Where the fit in any condition failed to reach significance (p = 0.05) the subject was excluded and replaced. Standard parametric tests (repeated-measures ANOVAs and Bonferroni-corrected t-tests) were used to assess differences across conditions with alpha set at 0.05 and appropriate corrections made for sphericity violations (as per Experiment 1d).

Results and discussion.

![Image of signals recorded following movement initiation](image)

**Figure 7.2.** Signals recorded following movement initiation in a typical double reach trial. Vertical lines demarcate the algorithmically derived strain gauge contact and release times (dotted for intermediate, solid for target). Note that the accelerometer picked up the target strain gauge’s vibration following finger contact. No formal calibration was carried out, but the experimenter’s online display also showed modifiable high/low range values around the eye tracker trace.

Exclusion of visual/auditory cues. In the pre-test, subjects averaged 10.7 correct answers for 60 Hz stimuli and 10.25 correct answers for 120 Hz stimuli (both out of 20 presentations). Individually, the binomial distribution
predicts that a score of 14 or less should occur 98% of the time (equivalent to the 5% high cut off value for a two-tailed test). Of 24 subjects, one scored 14 correct in the 60 Hz condition, while four scored 14 or 15 correct in the 120 Hz condition. Pooling across all trials, correct answers would be expected to fall in the region 219 to 261 95% of the time. Summed correct answers for both 60 Hz and 120 Hz stimuli were within these limits (257 and 246 respectively). The very slight trend to score above chance is therefore not conventionally significant. Even if some subjects were able to occasionally detect the presence of vibration without actually touching the target strain gauge, the magnitude of the effect is so tiny that it is unlikely to have had any influence upon timing judgements.

Movement characteristics. For short (15 cm) reaches, movements took an average of 251 ms. For long (50 cm) reaches, they took an average of 370 ms. For double reaches, the first (35 cm) component took an average of 295 ms, the second (15 cm) component an average of 247 ms, and subjects depressed the intermediate strain gauge for an average of 73 ms. Double reach movements therefore took a total of 615 ms. Figure 7.2 shows the signals from the accelerometer, strain gauges and eye tracker recorded in a typical double move trial, along with the times determined for strain gauge contact and release by the on-line algorithm.
**Time estimates.** Figure 7.3 shows the mean corrected time estimates across subjects for all four conditions. The control condition yielded subjective second estimates that differed significantly from the correct value of one second ($t = 2.49$, df = 23, $p = 0.02$). This finding might reflect an intensity bias across the target and reference stimuli used. The target stimulus oscillated at 120 Hz, whereas two of the three reference stimuli oscillated at 60 Hz. Intensity differences are known to affect duration judgements (Allan, 1979) and while no formal attempt was made to quantify subjective intensity in the current experiment it seems likely that the 120 Hz stimulus felt stronger. Moving to the pattern of data across conditions, it is clear that subjective second estimates are substantially reduced in all three movement conditions. This observation was confirmed by an ANOVA ($F = 20.41$, corrected df = 2, 46, $p < 0.001$) and follow ups which showed significant differences between all three movement conditions and control. The trend for estimates to be lower in long and double move conditions relative to the short move condition did not reach significance in the presence of a Bonferroni correction.

These results demonstrate a clear chronostasis-like effect for reaching movements; the perceived duration of a tactile stimulus, felt only after a reaching movement, is extended by 90+ ms relative to the same stimulus presented at rest. The situation appears analogous to the saccadic chronostasis results described in previous chapters, but the pattern of data across reaching conditions reveals possible differences. In saccadic chronostasis, the size of the effect scales with the size of the saccade. Experiment 1a showed this scaling to be approximately linear with movement duration (every extra 1 ms in motion resulted on average in a 1 ms increase in effect size). Such duration-dependent scaling would lead us to expect a difference of around 120 ms between the short and long reach conditions in the current experiment, far greater than that actually obtained. Power exceeded 0.99 to detect this difference as a post-hoc comparison ($\alpha = 0.008$). It is therefore clear that movement metrics are less precisely
reflected when chronostasis is measured for arm movements. In a sense this is perhaps not surprising. Although even saccades show some evidence of on-line correction (Moschovakis, Scudder, and Highstein, 1996) they represent perhaps the archetypal case of a ballistic movement and have a clear maximum in terms of their potential duration. This is not the case for arm movements. Rapid reaching movements do show broadly stereotyped velocity/acceleration profiles (Desmurget, Pelisson, Rossetti, and Prablanc, 1998) and are a less flexible class than arm movements in general despite displaying marked adaptation to sensory changes occurring after their initiation (Prablanc and Martin, 1992; Sheth and Shimojo, 2002). Nonetheless, they may last for periods of time over which a backdating process would seem somewhat implausible. A possible concern is that chronostasis might have arisen for more ballistic arm movements but not for those made with greater hesitancy and concern for accuracy. Such hesitant movements might have diluted chronostasis effects, including the differences across movement conditions. As a gross check against this possibility, scatterplots of effect size against average movement time were produced and correlation coefficients calculated across subjects. Neither correlations (r = -0.056 for short movements, r = -0.134 for long movements) nor visual inspection of scatterplots suggested a relationship between movement speed and effect magnitude. For saccades, backdating to a premotor event appears to be the norm. For arm movements, by contrast, backdating is to a point well after movement initiation, a difference that may reflect different underlying mechanisms.

The results of the double reach condition are difficult to interpret given the failure to obtain clear duration dependency in the other two reaching conditions. A priori, we might have expected an effect size that would be approximately equal to that found for short movements (backdating based on specification of the final movement) or that would reflect the entire duration of the double reach (backdating based on specification of the entire movement pattern). The latter prediction is unlikely, given the infinite temporal regress it implies for lengthy movement
sequences, and is not supported by the current data. There is however a hint that the first movement may have had some influence upon effect size. The magnitude of chronostasis for double reaches was very similar to that found for the single long movement and slightly greater than that obtained for the single short movement, although the difference between short and double conditions was only marginally significant (p = 0.087). The manner in which the first movement might have exerted any influence is not clear at this stage.

Experiment 6a employed a direct translation of the previous saccadic paradigm to a reaching situation, yielding a design in which reach-dependent tactile information was judged. In Experiment 6b, a very similar design was used to see whether reach-dependent chronostasis would also extend to alternative sensory modalities. A judgement was now required about the duration of a visual event that was triggered by the completion of an arm movement. Specifically, subjects now reached to a digital switch that triggered the fixation window to change colour sequentially. They then made judgements about the duration of the first colour-defined interval.

**Experiment 6b**

**Methods.**

**Participants.** Of the 27 participants who completed Experiment 6a, three were rejected because their data did not permit a valid subjective second estimate to be calculated in all conditions. The final sample comprised 24 subjects (15 male, mean age = 33.8, SD = 8.6). 19 had previously completed experiment 6a.

**Apparatus.** Apparatus was identical to that employed in Experiment 6a with the following exceptions. The target and intermediate strain gauges were replaced with two further digital switches mounted on mobile bases, and no vibrator was used. Headphones were not employed.
Design. The design was identical to that employed in Experiment 6a.

Procedure. The layout of equipment was identical to that described for Experiment 6a except that target and intermediate strain gauges were replaced with target and intermediate digital switches. Upon a verbal cue from the experimenter subjects made a rapid arm movement from the onset digital switch towards the target digital switch. In the double condition, they were required to briefly make contact with the intermediate digital switch en route. Their release of the onset digital switch initiated data acquisition for the trial. Initially, the on-screen window containing the fixation cross was black. When subjects’ right hands made contact with the target digital switch this window immediately changed colour to become white. It remained white for a variable period (400-1600 ms) before changing colour to become black again for a period of exactly 1000 ms. It then proceeded to alternate again between the two colours for periods of 1000 ms each (complete pattern: white-black-white-black). Because the end of the final black period was not marked by any visual event, and in order to minimise the possible intensity-dependent duration effects observed in Experiment 6a, subjects were required to pay attention only to the two white periods. The latter one-second white interval therefore comprised the reference stimulus. Subjects were required to judge whether the time they had seen the first white interval was longer or shorter than that for which they saw the later reference interval. They reported this judgement to the experimenter, who entered it before readying the next trial. A large window on screen presented the experimenter with a 1000 ms snapshot of signals recorded from the release of the digital switch. Signals from the accelerometer, eye tracker, intermediate and target digital switches were displayed along with vertical lines representing the times the computer had assigned to key events such as digital switch contact/release. The experimenter could choose to reject trials at this point (e.g. if a saccade appeared in the eye trace or contact times looked incorrect).
The duration of the first white period was controlled using a MOBS procedure (low boundary 400 ms, high boundary 1600 ms, initial presentation random 800-1200 ms, five reversals to terminate). The times at which the subject contacted the target digital switch and contacted/lifted off from the intermediate digital switch (double condition only) were calculated automatically. These estimated contact/release times were displayed against all traces. Trials were rejected automatically if contact times could not be determined or if the subject's eye signal (sampled for 1000 ms after movement initiation and once at each subsequent change of fixation screen colour) moved outside boundaries set and updated periodically by the experimenter. Additionally, in the double condition, trials were rejected if the period for which the subject had contacted the intermediate digital switch exceeded 300 ms.

Control blocks required no movement. Subjects simply rested their right hand on the target digital switch, with the experimenter initiating an identical sequence of four colour-defined periods that began 500 ms after a mouse key press. Blocks were of variable length, typically 6-20 trials. The first white period only began when subjects completed their movements, so no correction for movement time was necessary. The experiment took around 60 minutes to complete.

Statistical analyses. Statistical procedures were identical to those employed in Experiment 6a.

Results and discussion.

Movement characteristics. For short (15 cm) reaches, movements took an average of 311 ms. For long (50 cm) reaches, they took an average of 448 ms. For double reaches, the first (35 cm) component took an average of 349 ms, the second (15 cm) component an average of 301 ms, and subjects depressed the intermediate strain gauge for an average of 85 ms. Double reach movements therefore took a total of 735 ms.
Figure 7.4 shows mean subjective second values in all four experimental conditions. The control estimate was rather closer to 1000 ms than that found in Experiment 6a, perhaps suggesting that the instruction to attend only to the white stimuli was successful in counteracting stimulus intensity effects. More importantly, the pattern of results across conditions was quite different to that obtained for reaching movements to a tactile stimulus. Although all reaching conditions showed slightly lower subjective second estimates than the control condition, the magnitude of these differences was small (maximum of 41 ms in the double reach condition) and failed to reach significance in an ANOVA. This failure to obtain substantial chronostasis is unlikely to relate to experimental power, which was 0.97 to detect a difference of 90 ms (smallest effect obtained in Experiment 6a) as a post-hoc comparison ($\alpha = 0.008$; estimated based on the comparison with the greatest variability).

In accounting for this failure to obtain an effect we must consider all differences in procedure. The intended manipulation was of sensory modality (vision as opposed to touch) and this may have negated chronostasis, although the experience of the dead phone illusion in everyday life might weigh against such a conclusion (or at least imply that vision is somewhat special in being an exception). Additionally, Hodinott-Hill et al’s (2002) demonstration of a chronostasis-like effect for auditory stimuli
following a hand movement accompanied by a shift of attention suggests that stimulus modality might not have been crucial. It nonetheless remains a plausible candidate.

Movement parameters differed somewhat between Experiments 6a and 7b. In general, movements were rather slower in Experiment 6b, and this may have resulted in a failure to obtain chronostasis. Such a conclusion is weakened, however, but the failure to find any statistical relationship between movement speed and effect size across subjects in Experiment 6a. In Experiment 6b, an identical analysis was employed (calculating correlation coefficients between effect size and average movement duration in long and short reach conditions). Neither result was significant, although there was again a slight trend for correlations to show the predicted negative relationship (short: $r = -0.067$; long: $r = -0.212$).

A third possible cause was the change of instruction to concentrate on the identical comparison stimulus rather than all three comparison stimuli that followed the post-movement stimulus. If chronostasis only emerged when comparison is made with a train of post-movement stimuli this explanation would have merit, but the experiments reported in Chapter 6 demonstrate that, for saccadic chronostasis at least, the illusion occurs without regard for the nature of the comparison stimuli’s context (this result is obtained again in Experiment 6c).

A fourth difference is that the onset of the sensory event that was being judged in Experiment 6b was only an indirect result of the movement. Pressing the button caused the change of screen colour, but this link required an inference about cause and effect on the part of the subject because the stimulus change was mediated by an external relationship (in this case between the button and the computer). This was not the case in Experiment 6a, where the tactile information arose directly as a consequence of touching the vibrating strain gauge. It is also not the case in the dead phone illusion, where the arm movement brings the source of auditory stimulation within range of the ear. Hence the nature of the relationship between movement and consequent stimulus may be important.
A related issue is the degree to which the movement appeared to cause a sensory event in the two experiments. Pressing the switch clearly caused a change in screen colour, whereas touching the strain gauge in Experiment 7a would not have appeared to actually give rise to its perceived state of vibration. A causal inference of this type might suppress chronostasis.

A fifth possibility, however, must also be considered. In previous demonstrations of chronostasis, the onset of the post-movement stimulus has been uncertain in some sense. This is most clear in the case of saccadic chronostasis, where saccadic suppression is operating just prior to the required judgement, but is also the case for the reaching movements made in Experiment 6a. The tactile state of the strain gauge was unknown prior to the moment it was first touched. In Experiment 6b there was no uncertainty of this kind because subjects continuously fixated the stimulus and therefore had constant information about when it changed colour. Precise sensory information was therefore available to make a judgement about colour state, whereas in Experiment 6a the duration of a state had to be inferred from sensory information available only after a movement. The situation in Experiment 6b is reminiscent of one context in which the stopped clock illusion is rarely (if ever) experienced; when the ticking of the second hand can easily be heard. In this case the more reliable information from the auditory channel may be being used in preference to uncertain visual cues. In Experiment 6a subjects were being asked how long they actually felt the tactile stimulus for, but their sensory systems may have been answering with an estimate of how long the stimulus had actually occupied its current state. Experiment 6b provided clear information on this point.

These are all intriguing possibilities, open to empirical verification or rejection. We might ask, for example, whether chronostasis would emerge after opening a door onto a previously unseen visual scene (i.e. when the stimulus is visual but prior-state uncertainty exists)? However, the question was not addressed further in this series of experiments. Instead, Experiment 6c returned to the original saccadic paradigm. It was designed to replicate and extend previous movement-size related effects in saccadic
chronostasis and address the inconsistency between the demonstration of reach-dependent chronostasis in Experiment 6a and the failure to obtain chronostasis for head movement reported by Newport et al (2002).

Experiment 6c

Newport et al (2002) tested a subject with congenital ophthalmoplegia and reported that she exhibited no chronostasis when making rapid head movements to a visual target. This result can be integrated with the demonstration of reach-dependent chronostasis found in Experiment 6a in at least three ways. Firstly, it is possible that chronostasis occurs for some but not all movements, i.e. that it is present for arm and eye movements but not for head movements. Secondly, it may be that the effect is specific to a given sensory modality for a given movement, and that head movements might yield chronostasis for tactile (or auditory?) but not visual stimuli. Thirdly, it may be that Newport et al’s subject’s failure to experience chronostasis did not in fact relate to her head movements at all, but simply placed her at the tail of a distribution of normal performance. In the experiments reported throughout this thesis variability in time judgements has consistently been high, and a number of individual subjects have at one time or another failed to show evidence of chronostasis. Because subjects were typically tested with less than 100 trials in a given experimental condition (often considerably less) it is unclear whether these failures reflect genuine individual differences or simple measurement noise. Experiment 6c was therefore designed to search for statistical evidence of such individual differences in subjects completing repeated sessions of testing for saccadic chronostasis. It also fulfilled another purpose: by including short, long and double movement conditions it offered a replication and extension of Experiment 1a (movement-size dependency in saccadic chronostasis). This was intended to permit further comparison with the pattern of results obtained across conditions in Experiment 6a (i.e. the apparent lack of movement-size dependency).
Methods.

Participants. The experiment was completed by 5 subjects (three male, mean age = 21.6, SD = 8.8). Two were involved in the design of the study. All five had completed a number of previous experiments involving saccadic chronostasis, and one subject (NF) was selected on the basis that she had regularly failed to show an effect in previous experiments.

Apparatus. Subjects sat before a 22” CRT colour monitor refreshing at 60 Hz. Eye to screen distance was maintained at 41 cm using an adjustable chin rest. Horizontal eye movements were recorded using DC electro-oculography (7A22 amp: Techtronix; low-pass filtered at 100 Hz) and sampled at 200 Hz. Stimuli were black or red on a white background, subtending 1.1°. They consisted of crosses and open circles. The experiments were controlled by a PC interfaced with a 12 bit A/D card (National Instruments DAQ 1200).

Design. A repeated-measures design was employed with four conditions. The first short saccade condition involved a saccade of 15°. The second long saccade condition involved a saccade of 50° from a more extreme start point to an identical termination point. In the third double saccade condition the saccade began 50° from the termination point, with a transient fixation 15° before completion. The final control condition involved constant fixation at the eccentricity of the termination point. Trials from each condition were presented in separate blocks, with ten blocks per condition. Testing spanned five sessions on separate days with two blocks completed from each condition in each session. The eight blocks completed in a session were presented in random order.

Procedure. In long saccade blocks, subjects fixated a red cross on one side of the screen, initiated the trial with a mouse key press, waited at least 500
ms, then made a 50° voluntary saccade towards a black cross on the far side of the screen. Eye movement triggered the black cross to be replaced with a circle when the saccade had travelled one third of the distance to target. The circle remained on screen for a variable duration (200-1800 ms). It then disappeared, to be replaced by an identical circle (the comparison stimulus) after 500 ms. This stimulus was displayed for 1000 ms. Subjects indicated whether the time they saw the first circle was longer or shorter than that for which the comparison circle was displayed. The duration of the first circle was controlled by two independent MOBS procedures (low boundary 200 ms, high boundary 1800 ms, first presentation random 600-1400 ms, five reversals to terminate). The MOBS procedure that was to control stimulus duration on a given trial was selected randomly until one MOBS had terminated in order to prevent experienced subjects from being able to anticipate changes in presentation time. Blocks finished when both of the MOBS had terminated.

Saccade start/end points were calculated automatically using a velocity criterion; difference values between sample n and sample n-3 were compared to thresholds based on background signal noise. Trials where the first saccade recorded did not exceed 80% of the total distance recorded (summed across all detected saccades) were excluded on-line and repeated immediately. Trials in which subjects initiated their saccade within 500 ms of their key press were also rejected because the programme required this initial fixation period for proper functioning. Because signal noise was the primary cause of saccade rejection in previous experiments and the DC EOG amp used here had a relatively high low-pass filter setting an optional digital filter was incorporated prior to start/end point detection. A second order 30 Hz low-pass Butterworth filter was applied to the eye data in both forward and reverse directions to prevent any phase shift. Filter coefficients were derived using commercial software and implemented by the experimental software as described in the supporting literature (Matlab: the Maths Works Inc.) The filter was used occasionally (not all sessions) for two subjects.
For short saccade trials, an identical procedure was followed except that the initial fixation cross appeared 15° from the saccade target cross (consequently on the same side of the subject’s midline). For double saccade trials, initial fixation was as in the long saccade condition, but two target crosses were displayed. Subjects were required to make two saccades in rapid succession, pausing only very briefly at the intermediate target. The first saccade was 35° in extent, the second 15°. The change of target stimulus was triggered one third of the way into the second saccade (after four fifths of the total saccadic distance). Trials where the first and second saccades detected did not exceed 56% and 24% respectively of the total distance recorded were excluded. This criterion effectively excluded trials on which a corrective saccade was made to the intermediate target. In control (constant fixation) trials, subjects initially fixated a cross at equivalent eccentricity to the target cross used in all other conditions. It was blanked 400 ms after the subject’s mouse key press, then replaced after a further 100 ms by the to-be-judged circle, with subsequent stimulus presentation and subject responses as per saccade trials. Direction of saccade (saccade conditions: left to right and vice versa) or position of the fixation cross (control conditions: left or right) alternated every trial.

Blocks were of variable length, typically 12-40 trials (excluding those rejected). Twenty subjective second estimates per condition were recorded as the experiment proceeded (one for each MOBS termination). In the saccade conditions, each estimate was corrected post hoc to match the time the first circle was on screen following target foveation by subtracting the average time the eye was in motion following the triggered change to a circle (averaged across all blocks). In addition, a single subjective second estimate was obtained in each condition across all recorded trials using logistic regression (see Experiment 1a for details). In this case, the presentation time for each trial was corrected using its own eye movement and triggering data before entry into the regression. The experiment took around five hours to complete.
Figure 7.5. Time estimation data presented separately for four subjects over the course of five testing sessions. Separate lines show the four experimental conditions. Each data point represents the corrected termination value for a single MOBS procedure (two per block, two blocks per testing session).

Statistical analyses. Standard parametric tests (repeated and independent measures ANOVAs and bonferroni-corrected t-tests) were used to assess differences across conditions with alpha set at 0.05 and appropriate corrections made for sphericity violations (as per Experiment 1d).

Results.
**Saccade characteristics.** In the short saccade condition, saccades lasted an average of 53 ms and had a mean extent of 14.5°. In the long saccade condition, they lasted an average of 143 ms and had a mean extent of 46.3°. For the double saccade condition, the two saccades (mean extent 31.6° and 13.8°) took an average of 95 and 48 ms respectively, with an average intermediary fixation time of 198 ms. Hence the entire double movement took 341 ms.

**Individual differences in time estimates.** Figure 7.5 shows the corrected MOBS termination points (ongoing subjective seconds) across all ten blocks (= 20 MOBS values) for all four conditions. Results are displayed for only four out of five subjects because for one subject (CJ) a number of trials had to be rejected for technical reasons subsequent to her completion of the experiment. Although it was still possible to calculate subjective second values for her across all experimental trials (using logistic regression) block by block analysis depended on MOBS values which were calculated on-line and had therefore been contaminated by the trials that were later removed. For this reason her data was not included in the individual difference analysis (which depends on the assessment of variability over blocks) but was still used in the group analysis that follows. Figure 7.6 shows corrected time estimates across all

![Figure 7.6. Subjective second estimates calculated across all trials in each condition and displayed separately for each subject. The four conditions involved constant fixation, a 15° saccade, a 50° saccade or a double (35° + 15°) saccade.](image)
experimental trials for each subject in each condition, effectively summarising the data presented in Figure 7.5.

Looking at Figure 7.5, it is clear that all four subjects show considerable variability in their MOBS-derived estimates from block to block (and indeed often for the two MOBS procedures within a single block). No striking learning effects are evident across the ten blocks, although there is perhaps some sign of decreasing variability as the experiment progresses. Chronostasis is observable right across the duration of the experiment, although it does not arise in every block. Figure 7.6 summarises these data. For four out of five subjects, the magnitude of chronostasis is substantially larger in the long saccade condition compared to the short saccade condition (as found in Experiment 1a for a large sample). The double saccade generally shows an effect size only slightly larger than that obtained for short saccades. With close inspection, it appears that for four out of five subjects, the double saccade result is very similar to that found in the short saccade condition, while one subject shows an alternative pattern, with an increase in effect size relative even to the long saccade condition.

In order to assess individual differences in the pattern of chronostasis found across conditions, individual corrected MOBS termination values (shown in Figure 7.5) were entered into a two-way (4 x 4) independent measures ANOVA, with subject and condition as factors (subject = random, condition = fixed). The significant main effect of subject ($f = 30.743$, df = 3, 9, $p < 0.001$) was not considered a sufficient indication of individual differences, as it might simply reflect changes in any baseline bias for time perception (reflected in the control condition values) rather than differences in the magnitude of chronostasis. To provide evidence of individual differences, an interaction was therefore sought, and indeed emerged ($f = 3.198$, df = 9, 304, $p = 0.001$). Hence subjects displayed significantly different patterns of subjective second estimates across conditions, regardless of their overall bias. It is noteworthy, however, that all of the subjects tested here did show substantial chronostasis effects.
overall. In light of this result, it seems that Newport et al.'s failure to detect any effect for their subject with congenital ophthalmoplegia may reflect a genuine failure of chronostasis under conditions in which head movements are made to fixate a visual target. This interpretation, of course, depends upon the number of trials these authors used to assess the illusion. The present data suggests that chronostasis emerges reliably for eye movements with around 200 trials per condition. Regarding the majority finding of a difference between the short and long saccade conditions, only subject JR showed mean values that were very similar in these conditions. It is not, however, safe to conclude that JR does not experience saccade-size dependent chronostasis. Based on his individual corrected MOBS termination values, power was only 0.6 to detect the predicted effect size of 90 ms ($\alpha = 0.05$).

The finding of robust individual differences across subjects also has relevance for an issue arising throughout this thesis; the comparability of results in different conditions of separate experiments. For some of the experiments reported, post-saccadic subjective second values that have been taken as evidence of chronostasis have been numerically similar to control values obtained in other experiments. Similarly, the magnitude of obtained chronostasis effects has often shown considerable variation across experiments. The approach taken here has been to make comparisons only within a single experiment. This approach is validated by the current finding, which strongly suggests that differences in sample composition across experiments would make direct comparison problematic.

*Group effects.* Figure 7.7 shows mean corrected time estimates across subjects for each of the four experimental conditions. As expected from individual difference data, a large difference is evident when comparing the saccade conditions to control. The control estimate itself is quite low, mainly reflecting the contribution of one highly biased subject (NF) in this small sample. Additionally, the long saccade condition shows a reduced subjective second relative to short and double saccade conditions. To assess
reliability when generalising to the population at large, data were entered into a one-way repeated-measures ANOVA which revealed a significant difference across all conditions ($f = 9.891$, corrected df = 2,6, $p = 0.015$). Given the small sample, bonferroni-corrected post-hoc tests lacked sufficient power to further discriminate between conditions, although a number of comparisons approached significance (control/short, $p = 0.058$; control/long, $p = 0.062$; short/long $p = 0.127$).

These data offer a replication of the pattern of data obtained in Experiment 1a, in which long saccades yielded a larger effect size than short saccades. Once again, the difference between these conditions was roughly commensurate with the difference in mean saccade durations, although for this sample it rather exceeded it (difference in mean subjective seconds = 131 ms; difference in mean saccade durations = 90 ms). Following both long and short saccades, therefore, subjects felt that they had perceived the post-saccadic stimulus in excess of 100 ms before they began to move their eyes.

The double saccade condition offers new data that is challenging to interpret. Although it yielded a mean subjective second that fell between those found for the short and long saccade conditions, this largely reflected the contribution of a single subject, with other subjects displaying subjective second estimates similar to those found in the short saccade condition. In terms of the dichotomous hypotheses presented earlier, it is tempting to
conclude that chronostasis emerged only relative to the second saccade for most subjects, whereas for subject JM it reflected planning of the entire double movement. However, subject JM’s data pattern is not completely consistent with this interpretation (the increase in effect size should be smaller between short and long conditions and greater between long and double conditions) and any account based on a single exceptional case in a small sample must remain speculative.

General discussion

The experiments reported here were designed to search for evidence of chronostasis following reaching movements. In Experiment 6a, chronostasis was demonstrated for judgements about the duration of a vibrating tactile stimulus subsequent to such a movement. Chronostasis emerged for short, long and double reaching movements with a similar magnitude despite a small trend towards increasing effect size with movement extent. In Experiment 6b, identical reaching movements were performed with movement termination triggering a change of screen colour. Little if any chronostasis was observed. In Experiment 6c, saccadic chronostasis was assessed over a longer period of testing. Significant individual differences emerged in the magnitude of chronostasis across experimental conditions, but all five subjects clearly experienced the illusion. On average, its magnitude appeared to depend upon saccade extent.

A comparison of Experiments 6a and 6c yields both interesting similarities and striking differences. Chronostasis, defined as a subjective lengthening of the post-movement stimulus, is evident in both cases, suggesting that some more general process might be underlying a change in temporal perception subsequent to both saccades and manual reaches. The magnitude of the effect for reaching movements is generally comparable to that obtained in previous saccadic chronostasis experiments, with the subjects in Experiment 6c exhibiting a rather larger illusory effect than is typical. However, the pattern of results across conditions differs. For
saccadic movements, the effect has previously been characterised as the predating of post-saccadic stimulus onset to a moment just prior to movement initiation. Experiment 6c is in broad agreement with this finding. However, Experiment 6a shows that an analogous explanation of reach-dependent chronostasis would involve predating only towards some point mid-way through the reaching movement. There is a suggestion, but no statistically compelling evidence, that the effect may be slightly larger for longer movements, but a linear increase with movement duration is not evident. This suggests that the processes underlying the two effects (saccadic and reach-dependent chronostasis) may be somewhat different. It is also noteworthy that the new double move/double saccade condition introduced here appears to have yielded slightly different data patterns for reaching and saccades. Statistical support is limited, but for reaching, double movements appear to yield estimates similar to long reaches, whereas for saccades they tend to be close to short saccades. Interpretation is muddied by the difference in the long/short effect between experiments, but it is tempting to conclude that the first movement is actually more significant for double reaches than for double saccades. This may reflect the much larger pause time between saccades (mean = 198 ms) compared to reaches (mean = 73 ms). It might for example be that the double move was planned in its entirety from the outset, whereas the saccade was not, or that any chronostasis related to the first movement decayed in some manner following its termination but still interacted with the second movement.

The individual difference data from Experiment 6c are perhaps also surprising in the context of the previous explanation of saccadic chronostasis. It has been assumed that predating of the post-saccadic stimulus is to some specific pre-motor event. It seems odd (but not impossible) that such an event should vary widely in its timecourse between subjects. However, subjects’ internal estimates of such a point might vary considerably, and it is not clear what manner of representation is being relied upon to produce chronostasis. Certainly the demonstration of inter-subject variability is not unique in research on timing. Strong and stable
individual differences are common when subjects attempt the precise temporal localisation of stimuli (e.g. Stone, Hunkin, Porrill, Wood, Keeler, Beanland, Port, and Porter, 2002) often being taken as evidence against simple latency difference accounts (Mueller, Aschersleben, Koch, Freund, and Prinz, 1999). Individual differences are not insurmountable for a backdating account, but might seem more naturally explained via the addition (or substitution) of another component such as the transient arousal account previously discussed in Chapter 6.

In comparing Experiments 6a and 6b, a number of possible differences in experimental procedure were discussed to account for the failure to obtain reach-dependent chronostasis for judgements about a visual stimulus. While the specific linkage of a particular class of movements to a particular sensory modality is one possibility, another strong contender must be the failure to implement conditions of onset uncertainty in Experiment 6b. Whichever interpretation is preferred, it is clear that chronostasis depends not simply upon a movement but upon some specific combination of movement-related and sensory parameters. The nature of this chronostasis-eliciting context and the degree to which various experiments (including those of Hodinott-Hill et al, 2002, and Newport et al, 2002) can be subsumed within such a general explanation will be more fully discussed in Chapter 8.
Chapter 8. General discussion

Before proceeding to discuss the issues raised by the seventeen experiments presented here, a brief chapter by chapter summary is offered. A comparison of experimental methods and results is presented in Table 8.1. A single general methodological concern and seven areas of interest will then be dealt with in no particular order prior to some brief concluding remarks. Because these areas of interest overlap, earlier discussions will tend to impinge upon those presented later, and consequently enjoy considerably greater coverage. This is not meant as a judgement on their relative worth.

<table>
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</tr>
<tr>
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Table 8.1. Summary of experimental methods and results.
In Chapter 2, the basic phenomenon of saccadic chronostasis was established. When subjects saccaded to a counter that incremented during the period their eyes were in motion they tended to overestimate the duration of the first digit they subsequently perceived. The size of this overestimation varied with saccade extent, suggesting the hypothesis that the perceptual onset of the first post-saccadic stimulus effectively occurred prior to the initiation of the eye movement. A first control experiment approximately reproduced the visual conditions occurring during the saccade by having the counter move rapidly towards fixation. No chronostasis was observed, suggesting that the effect depended upon the movement and was not simply a reflection of uncertainty about a stimulus onset. A second control experiment manipulated the point at which the counter increment occurred, but failed to affect the size of the illusion, suggesting that this stimulus change itself was neither perceived nor used as a cue to initiate duration judgements. A final experiment required subjects to make a deliberate shift of covert attention prior to their saccade, a manipulation that had no influence on the size of the resulting illusion. To the extent that this endogenous attention shift could be considered equivalent to (i.e. a replacement of) that typically occurring prior to a saccade, chronostasis did not appear to depend upon an attentional mechanism.

In Chapter 3, the effect of manipulating specific features of the visual scene was examined to determine the conditions under which saccadic chronostasis might arise. When the counter to which subjects directed their eyes was shifted mid saccade and subjects reported awareness of this shift, chronostasis was eliminated. When the shift went unnoticed, a partial effect resulted. This result suggested that implementation of the process yielding chronostasis depended upon the perceived spatial continuity of the saccade target, i.e. that an assumption of form continuity could be overridden by the perceived failure of spatial continuity for this object. A control experiment indicated that the impairment of saccadic chronostasis was selective; it did not arise when a distracting character
appeared during the saccade, so was unlikely to result from some kind of generalised distraction. A final experiment provided suggestive evidence that shifting other salient objects represented across a saccade might also disrupt saccadic chronostasis. These experiments raised interesting questions about the relationship between chronostasis and cross-saccadic visual memory.

In Chapter 4, saccadic chronostasis was investigated for moving stimuli. The illusion was found to arise when the post-saccadic duration of a continuously present erratically moving stimulus was judged, at least for relatively slow velocities. Two possible accounts of any interaction between chronostasis and perceived position for a moving stimulus were discussed: the movement backfill and correct localisation accounts. In addition, a hybrid of the two accounts was considered, and an alternative framework focussing on multiple independent representations (a non-unitary consciousness) was briefly discussed. The data presented were unable to distinguish clearly between these alternatives, primarily because of crucial methodological differences (e.g. the saccade target not having been present in the pre-saccadic view) that might have prevented chronostasis from arising in the experiments assessing perceived position.

In Chapter 5, two ideas were explored relating to the multiple and dissociated nature of timing behaviour and event-time representation. The first was that saccadic chronostasis might influence some, but not all, timing mechanisms. Experimental evidence in favour of this view came from a comparison of perceptual judgements and tapping behaviour in a paradigm where both were performed together and also in isolation. Chronostasis failed to influence tapping behaviour, but veridical tapping behaviour did not override the illusion either, suggesting that separable and differentially influenced clocks were performing the two tasks. The second idea considered was that saccadic chronostasis might alter representations of the onset/offset times of certain events in an isolated manner, leaving an inconsistency between the perceived ordering of affected and unaffected events and the shift of affected events implied by chronostasis. Essentially,
this position suggested that the contents of consciousness depend upon the question that is being asked, with different questions yielding different and sometimes mutually incompatible answers. Evidence came from a temporal order judgement experiment with tactile stimulation delivered in the temporal region around a saccade. Data were broadly consistent with the dissociation view, but the negative result in combination with a number of methodological shortcomings precluded any strong conclusion from being drawn.

Chapter 6 again reflected two rather different experimental approaches, the common theme being an attempt to expand saccadic chronostasis beyond the specific conditions of a voluntary saccade to an ongoing discretely changing stimulus (i.e. a digital second hand). The first experiment employed a slightly different judgement, between the post-saccadic stimulus and a single comparison stimulus. In addition, the duration of the comparison stimulus was varied between 333 ms and 1333 ms. Saccadic chronostasis arose for this new stimulus arrangement at all comparison stimulus durations, suggesting that it depended on neither a specific post-saccadic context nor a minimum exposure time for the post-saccadic stimulus (unless it be extremely short). The size of the effect varied slightly across reference stimulus durations, suggesting both constant and proportional effects, although direct statistical support for either position was lacking. The hypothesis that the onset of the post-saccadic stimulus was predated to a moment before movement initiation therefore received mixed support. Purely arousal-based and attentional accounts fared no better. In two further experiments, saccadic chronostasis was assessed following reactive saccades (either centrally or peripherally cued) and anti-saccades. The illusion emerged in all conditions. These findings suggested that the signal used to cue or otherwise influence time judgements emerged late on, near the point of movement specification, and was little influenced by the cued/intentional nature of the saccade task. Anatomically, the generality of the effect pointed towards regions such as the brainstem burst generator and superior colliculus.
Finally, in Chapter 7 an analogous manual chronostasis illusion was demonstrated for reaching movements to a tactile stimulus. This effect showed only limited dependence upon movement parameters and appeared to reflect backdating to a point during rather than before the reaching movement. In a subsequent experiment, the illusion was not obtained for reaches that resulted in a change in a visual stimulus. A final experiment replicated the coupling found previously between movement size and effect size for saccadic chronostasis, and demonstrated clear individual differences in the magnitude of the illusion across conditions. The illusion did however emerge for all subjects tested. These experiments suggested that the phenomenon of chronostasis might be more general than had previously been suspected, with some striking differences emerging between saccadic and manual data. This finding will be taken up after a brief methodological aside.

Sample composition across experiments. Some attempt has been made in earlier chapters to indicate the degree to which subjects were repeatedly recruited across experiments. To summarise, it is fair to say that while the subject base varied considerably over the entire research period, many subjects completed a number of related experiments. Subjects were often informed of the purpose of experiments after they had completed them, so many were non-naïve, in the sense of having knowledge of the chronostasis effect. They did not, however, have detailed knowledge of specific experimental hypotheses before participating in particular experiments. Subjectively, the chronostasis illusion is compelling despite the prior knowledge that it is not objectively real. Equally, for subjects completing their first chronostasis experiment and with no knowledge of the illusion, a robust effect was typically found. It therefore seems unlikely that the results presented here were seriously compromised by repeatedly testing participants, although it is possible that some element of response bias may have occasionally influenced decisions.
Generality verses specificity of chronostasis. Although the majority of this thesis has concentrated on saccadic chronostasis, Chapter 7 introduced important new data regarding an analogous illusion for reaching movements to a vibrating tactile stimulus. This data can usefully be reviewed in the context of two recent papers from other groups following up on the saccadic chronostasis findings reported in Chapters 1 and 2.

Newport, Osborne, Wakely, Walsh, and Jackson (2002) reported an absence of chronostasis in a subject with congenital ophthalmoplegia who made rapid head movements in place of saccades. In a second experiment, they also demonstrated that the same subject failed to demonstrate the illusory compression of visual space typically found just prior to and during saccades when visual references are present (Burr, Morrone, and Ross, 2001; Ross, Morrone, and Burr, 1997; Ross, Morrone, Goldberg, and Burr, 2001; Lappe, Awater, and Krekelberg, 2000). Here, briefly presented visual targets are mislocalised in the direction of the saccade target. Newport et al.'s discussion provides an interpretation of chronostasis that is at the specific (as opposed to general) end of the spectrum. They imply that chronostasis and the perisaccadic compression of visual space are linked phenomena, probably relating to shifts in receptive fields of cells in the homologue of area LIP (Duhamel, Colby, and Goldberg, 1992). They suggest that the rapidity of saccades requires the predictive updating of relative position, a requirement that is absent in slower movements (like those of the head) where proprioception is sufficient for this purpose. Hence they predict chronostasis (and perisaccadic compression) only for rapid movements planned in occulocentric co-ordinates.

A contrasting, very general interpretation is provided by Hodinott-Hill, Thilo, Cowey, and Walsh (2002). Although their study, more fully described in the following section, employed a shift of spatial attention as its main experimental variable, they opt for a discussion in terms of an arousal effect operating at the level of the hypothetical pacemaker-accumulator internal clock. This explanation synthesises findings from previous saccadic chronostasis experiments and their own auditory chronostasis experiment
with those of Rose and Summers (1995). In the latter study, subjects judged
the duration of the first stimulus in a train of four square light patches
presented at fixation and typically overestimated it. Hodinott-Hill et al.
suggest that the common factor is an increase in task demands which gives
rise to a temporary increase in the speed of the internal clock (an arousal
effect). This in turn leads to the overestimation of a given interval.

Newport et al.'s (2002) specific account clearly faces problems
dealing with the manual chronostasis effect reported in Experiment 6a. The
immediate recourse would be to suggest that, despite the analogous thinking
that gave rise to the experimental design, manual chronostasis differs from
saccadic chronostasis in a fundamental way, or is an artefact of some kind.
The differences between the illusions in relation to movement parameters
give some weight to such an argument, but the similarities are also striking,
and no artefactual explanation is immediately forthcoming. A detailed
consideration of the marriage of parietal cell activity, spatial compression
and chronostasis presented by Newport et al. is perhaps helpful. The
proposed link between chronostasis and parietal cell receptive field shifts
(or indeed the similar shifts found in frontal eye fields and superior
colliculus; Ross et al., 2001; Umeno and Goldberg, 1997) seems quite
plausible, if far from certain. In effect, the brain is simply assuming that the
new stimulus which will occupy fixation after the saccade is fully perceived
from the moment the relevant neurons first detect its presence, i.e. when
their receptive fields shift just before the saccade. Better information about
the state of that stimulus must of course await its actual arrival at the fovea,
but initial perception is judged to have occurred prior to eye movement. The
link between spatial compression and these shifts is perhaps more fraught;
however, despite having been alluded to in a number of articles (e.g. Ross et
al., 2001) and requires a close look at the supporting data.

The finding of perisaccadic compression is in fact a recent addition
to a previous literature on perisaccadic mislocalisation (reviewed in Schlag
and Schlag-Rey, 2002). For saccades made in darkness, briefly flashed
stimuli are mislocalised in the direction of the saccade by up to 70% of
saccade extent. This error is maximal at saccade onset and may reverse direction towards the end of a saccade. A reasonable assumption is that any estimate of spatial position must arise from the integration of an eye

![Figure 8.1. Schematic of the expected shift in the perceived position of a stimulus when retinal information is combined with a flattened internal representation of eye position. The arrow at the top shows the spatial position of the stimulus. The left-hand figure shows correct localisation during a fixation. In the central figure, the eye position signal (dashed line, bottom left graph) is ahead of actual eye position (solid line in bottom left graph). This leads to misperception in the direction of the saccade. In the rightmost figure, eye position signal lags actual eye position, causing a smaller misperception opposite to saccade direction.](image)

position signal (eye position relative to head, simplifying to ignore the head-body transformation) with the retinal stimulation pattern. Such a process is required to achieve space constancy, at least in the absence of retinal (visual) cues (Sperry, 1950; Von Holst and Mittelstaedt, 1950). Plotting mislocalisation errors as a function of time (relative to saccade onset) then correcting for the actual position of the eye, it is possible to construct a hypothetical function for the eye position signal. Ignoring the added complication of any transmission delay between retinal stimulation and representation (which would require a rightwards shift) this function can be thought of as the internal representation of eye position. It approximates the actual eye movement, but is somewhat flattened; it begins to rise well before
the saccade and reaches a maximum after saccade termination. Mislocalisation can therefore be thought of as a measure of the system’s error in solving the space constancy problem. This explanation is presented in schematic form in Figure 8.1.

Turning to neurophysiology, parietal cells with shifting receptive fields were initially also linked with mechanisms of space constancy (Duhamel, Colby, and Goldberg, 1992). However, it is clear that their predictive remapping is not equivalent to (or an implementation of) the combination of eye position signal and retinal information discussed above. Figure 8.2 graphically demonstrates that receptive field shifts do not solve the space constancy problem because their action implies a spatial shift that is equivalent to that produced by the actual saccade (i.e. causes visual
stimuli to shift in a direction opposite to the saccade). This process is also clearly not the basis of traditional mislocalisation effects, which cause stimuli to appear displaced in the same direction as the upcoming saccade. Shifting receptive fields simply move the requirement for an integration of eye position signal and retinal information forward ahead of an upcoming saccade. Their functioning seems to be predictive of upcoming visual events (effectively overcoming the sensory delay when a new stimulus appears) and may permit the advanced planning of future saccades in oculocentric co-ordinates without reliance upon the previously discussed spatial frame of reference (Umeno and Goldberg, 1997).

When visual cues are present, the situation is even more complex. Rather than simple unidirectional mislocalisation, observers experience the aforementioned compression of visual space such that stimuli presented at the same time but in different positions may be reported to shift in opposite directions (towards the saccade target position; Lappe, Awater, and Krekelberg, 2000). This is perhaps not so surprising. The presence of rich retinal signals clearly has a major effect on spatial localisation. Manipulations of extra-retinal signals known to give rise to mislocalisation in darkness (e.g. passive eye deviation) have a much reduced effect in the presence of a structured visual environment (Desmurget et al., 1998). Extra-retinal cues lack the sufficient precision to account for space constancy in natural scenes, and the system seems sensitive to relative rather than absolute shifts of key visual markers (Bridgeman, Van der Heijden, and Velichkovsky, 1994; Currie et al., 2000). Indeed, the brain appears to default to an assumption of saccade target spatial constancy when the target is detected immediately after an eye movement (Deubel, Bridgeman, and Schneider, 1998). It has therefore been suggested that both eye and arm movements may be planned primarily in oculocentric (allocentric, relative)

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1 If we consider a combination of receptive field remapping and the use of the eye position signal, it becomes apparent that an early (predictive) representation of eye position would cancel out remapping effects and lead to veridical perception. An early eye position signal with a gain close to 2.0 is then required to yield spatial mislocalisation effects, suggesting that either the remapping account presented here is too simplistic, or this process is not functioning under conditions which yield traditional (unidirectional) mislocalisation.
co-ordinates when vision is permitted, but that a separate (egocentric, absolute) frame of reference is employed in its absence (Husain and Jackson, 2001). The idea of occulocentric planning has received recent support from neurophysiological recordings in the monkey parietal reach region (Batista, Buneo, Snyder, and Andersen, 1999; Buneo, Jarvis, Batista, and Andersen, 2002). It is plausible, therefore, to map mislocalisation errors like those found with access to vision onto occulocentric planning strategies. Co-ordinate transformation is then delayed until movement specification. As mentioned previously, the predictive shift of receptive fields in LIP seems well designed to facilitate occulocentric planning in the absence of complete spatial transformation. By contrast, an absence of relative visual cues forces the system to rely on an alternative egocentric system in which the eye position signal is used to establish a target in egocentric co-ordinates prior to movement planning. In this case, the plan is already formed in egocentric space and no further transformation is required.

Recently, a link has been drawn between shifting receptive fields and perisaccadic compression (Ross et al., 2001; Husain and Jackson, 2001). Rather than applying the rather simplistic logic of Figure 8.2, these authors note that receptive field shifting is not an all or none process. Some parietal cells maintain their pre-saccadic receptive fields throughout a saccade, while others respond to stimuli at both pre-saccadic and remapped retinal locations. It has been suggested that this effective expansion of receptive fields might underlie spatial compression. This possibility has intuitive appeal, although any attempt to work it through in a simple diagrammatic manner reveals just how vague it currently is. We might perhaps think that an equally or even more likely substrate would be the receptive field shifts found in area V4 (Tolias, Moore, Smirnakis, Tehovnik, Siapas, and Schiller, 2001). These cells display shrinking receptive fields that shift in the direction of the saccade target (rather like spatial compression) rather than in the direction of the saccade itself (rather like unidirectional mislocalisation). Unfortunately, the simple prediction based on this type of shift would be for an expansion, not a contraction, of visual
space near the saccade target. If nothing else, this observation should alert
us to the difficulty of mapping physiology onto psychophysics. Nonetheless,
the relationship between parietal cell activation and spatial compression
remains intriguing.

To summarise, then, as a crude dichotomy:

1. Light = relative allocentric planning = compression = parietal
   receptive field shifts.
2. Dark = integration with eye position signal followed by absolute
   egocentric planning = unidirectional mislocalisations.

Set out in this manner, Newport et al.’s (2002) position on the
linkage of chronostasis, receptive field remapping and perisaccadic
compression becomes clearer. The characterisation attempted here has
passed over a number of difficulties (not least contrasting data and theory on
how the two systems are integrated, how cognitively penetrable they are and
under what conditions each dominates). To take one example, Burr,
Morrone, and Ross (2001) found that saccadic compression disappeared
when pointing movements were conducted with the eyes closed. This is in
partial agreement with the above framework, but a simple application of its
logic would lead us to expect that rather than disappearing, compression
errors should have been replaced with eye-position-dependent unidirectional
mislocalisation under these conditions. Hence the situation is messy, but the
account is broadly plausible.

Returning once again to the demonstration of manual chronostasis in
Experiment 6a, can some rapprochement be reached between Newport et
al.’s account and these data? Perhaps so, if only speculatively. It may for
example be possible to steer some middle ground by considering the role of
predictive mechanisms in arm movements. As discussed previously,
unidirectional mislocalisation data for eye movements suggest that the
internal representation of eye position precedes actual eye movement.
Dassonville (1995) has obtained analogous data for arm movements. In his
experiments, subjects were required to move their arms rapidly across the workspace without vision. A tactile stimulator positioned at the fingertip presented a brief stimulus at some point around the time of such a movement. Subjects were required to return their arms to the position at which they felt it had been located when the tactile stimulus was delivered. They consistently indicated a position ahead of the place their arm had actually been, suggesting that in attempting to judge the coincidence of arm position and buzz their internal representation of arm position led that of the tactile stimulus. Hence, just as eye position signal leads eye movement, so arm position signal leads arm movement, at least in darkness.

Given that the Newport et al. account is based upon different planning processes in relative light and darkness, it could be argued that this data is not directly relevant. It is however suggestive, implying that arm localisation can be predictive. The above discussion of eye movements placed considerable emphasis on receptive field shifts. Here too, there is evidence relevant to arm movements. Graziano, Yap, and Gross (1994) have shown the existence of bimodal neurons in monkey ventral premotor cortex, possessing both visual and somatosensory receptive fields. Many show visual receptive fields that move when the somatically represented arm is repositioned. This would appear to indicate a rather coarse coding of visual stimuli in a co-ordinate frame centred on the hand. There are clearly a great many differences between these shifts and those found to precede eye movements in area LIP (most notably the fact that they are not transient, i.e. do not return to standard retinal co-ordinates after movement). However, they might serve a rather similar function. Receptive field shifts in LIP and related areas have been linked to a saccadic system that can plan further movement immediately (or even predictively) in a preferred reference frame. Premotor neurones might allow a similar operation for the arm (Umeno and Goldberg, 1997). There is currently no data regarding the timecourse of premotor remapping, as arm repositions rather than arm movements were studied, but given psychophysical data like that of Dassonville (1995) it is at least conceivable that these shifts might arise in a
predictive manner. The receptive field shift that causes the cell to respond to
the reach target as a visual stimulus might act as a backdating point in
manual chronostasis analogous to the pre-saccadic shifts hypothetically
linked to saccadic chronostasis. If we assume a shift time that mirrors the
sluggishly predictive arm position signal (rather than shifting suddenly in
advance of and over the entire extent of the arm movement, as for saccades)
we could explain why manual chronostasis does not scale with effect size.
Predating would be expected to be towards the point when the relevant
receptive field shift occurred (the one that brought the buzzer into the
receptive field) and this would not be expected to occur until near the end of
the arm movement.

This account is clearly speculative in the extreme, but as we have
seen, the corresponding argument for saccades is less than certain. When the
function of chronostasis was first considered early on in this research
programme, one evolutionary explanation briefly entertained was that the
illusion might offer the organism a competitive advantage by extending the
perception of a potentially dangerous perceptual event. The concept was
rejected because simply fooling consciousness (extending the perception of
duration) would not appear to offer a genuine behavioural benefit. However,
the broad receptive field shift account presented here offers something of a
resurrection for this theory. Chronostasis may not just fool consciousness; it
can reflect a fundamental post-movement perceptual process designed to
maximise the subsequent rapidity of response (be it eye or hand movement)
to behaviourally salient stimuli.

Turning now to the arousal interpretation presented by Hodinott-Hill
et al. (2002) it seems appropriate to first expound the strengths of such an
account. In positing an effect on the pacemaker of a hypothetical internal
clock, the arousal account is both theoretically simple and extremely broad
in its explanatory potential. It establishes chronostasis within a well-
researched cognitive model and links it with other illusions of time
perception. The account is built upon data from three studies: Rose and
presented here in Chapters 2 and 3) and Hodinott-Hill et al. (2002). It is argued that in the case of the Rose and Summers illusion (which occurs for a train of four squares of light flashed in succession) the onset of the first square is arousing relative to later stimuli. No effect is obtained in the superficially similar constant fixation trials of saccadic chronostasis experiments because the first judged interval is preceded by a stimulus in an identical position (a “0”) reducing arousal. In these experiments, an effect emerges following eye movement because saccadic suppression makes the post-saccadic onset seem like the appearance of a new stimulus, or possibly because the movement itself (a “task demand”) leads to arousal. Finally, in Hodinott-Hill et al.’s own auditory chronostasis study, the shift of attention creates an additional arousing task demand that speeds the pacemaker. Much of the arousal account’s appeal comes from explaining these various data in one framework. Unfortunately, two of these three studies would seem to be incompatible with this account, suggesting that the wide ranging links the theory proposes may be over ambitious:

1) Rose and Summers (1995) explicitly reject an arousal account of their data in a broad ranging discussion of possible low and high level explanations. Of particular interest are three of their findings. Firstly, their illusion showed no dependency upon quite extreme changes in stimulus intensity and contrast. Very bright stimuli would be expected to be more arousing. Secondly, their illusion showed no dependency upon inter-flash interval (200 versus 600 ms). The arousal effect would have to be extremely potent but very short lived to explain this result (see discussion in Experiment 5a). Thirdly, their illusion shows no tendency to habituate, whereas arousal would most likely do so.

2) Experiment 1a showed that saccadic chronostasis depended upon movement extent. This requires us to posit that longer movements are proportionally more arousing. In Experiment 1b, no effect emerged for a stimulus moving rapidly towards
fixation, a sequence that would seem quite likely to cause arousal. More critically, the experiments reported in Chapter 3 demonstrated that shifting the saccade target mid saccade could prevent saccadic chronostasis. This event would seem, if anything, more arousing rather than less so. It strongly suggests that the illusion is tied to specific qualities of the post-saccadic stimulus.

The basic platform for the arousal account therefore appears questionable. In addition, much evidence presented in earlier chapters but not yet published argues against the simple role of arousal. To be specific:

1) Experiment 5a varied reference stimulus duration in an explicit attempt to map saccadic chronostasis onto the internal clock model. Neither a simple (proportional) arousal account, nor one incorporating a transient, decaying arousal function fitted the data as well as the combination of constant and multiplicative components suggested by linear regression.

2) Experiment 4a demonstrated a dissociation between the timing underlying the perceptual experience of chronostasis and that controlling subjects’ tapping behaviour at the same time. Arousal effects are known to effect both perceptual and motor timing to a similar degree (e.g. Treisman, Faulkner, Naish, and Brogan 1990; Treisman, Faulkner, and Naish, 1992), so why was the influence of chronostasis selective in this experiment?

3) Experiment 5c contrasted reactive saccades to a peripheral onset (pro-saccades) with reactive saccades in a direction opposite to a peripheral onset (anti-saccades). Anti-saccades are cognitively demanding. It would therefore seem intuitively likely that they are more arousing than pro-saccades, which feel effortless. Chronostasis, however, occurred with equal magnitude for both kinds of saccade.
4) Experiments 5a, 5c and 6c used a single empty circle as a reference stimulus. In the control condition, a brief blank was inserted between the fixation cross and the variable (judged) stimulus. This roughly equated the stimulus-related arousal between saccade and control conditions (i.e. approximately mirrored saccadic suppression in the constant fixation trials). Chronostasis still emerged, so if arousal was responsible, it must have arisen purely from the movement.

5) In Experiment 6b, no (or very little) effect was found when reaching to a button that triggered a change of screen colour. In Experiment 6a, a reliable effect was obtained when reaching to a buzzing tactile stimulus. It is not at all clear why the tactile stimulus (or preceding movement) should be highly arousing while an obvious colour change (black to white) for a large section of space around the fovea (preceded by the same movement) should not be, given that both events were entirely predictable.

These observations argue strongly against the broad arousal account proposed by Hodinott-Hill et al. They tend to reject (rather than bolster) the conclusion that the illusion described by Rose and Summers (1995) is related in any simple fashion to chronostasis and is explicable in the same terms. It may be premature, however, to entirely rule out the influence of arousal in chronostasis experiments. The aforementioned objections simply suggest that it may be supplementary to some other process, like that discussed previously in relation to the work of Newport et al. (2002). On grounds of parsimony, we should prefer a single explanation rather than one incorporating elements of various theories. Nonetheless, the combination of an arousal account with some alternative, more specific explanation would seem to offer some striking benefits. It might help to account for the proportional (multiplicative) component found in addition to a constant effect in Experiment 5a (manipulation of reference stimulus duration). An
arousal component might also offer an explanation of the individual differences demonstrated in Experiment 6c, and explain why some small residual effect is obtained when chronostasis has been prevented (Experiment 2a: counter jump) or has not been elicited (Experiment 6b: reach to trigger a visual change). Finally, arousal may have had some part to play in the general tendency for control estimates to drop below the actual presentation time of reference stimuli. It should therefore perhaps be considered as a secondary factor in chronostasis experiments.

The role of movement and attention. Although the title of this thesis ("temporal illusions subsequent to movement") is deliberately vague regarding the causal role of action for chronostasis, the general experimental approach has emphasised the importance of movements in eliciting the effect. An issue which must be addressed, however, is whether movement is really important at all, or has simply gained the limelight via its association with shifts of spatial attention. The experimental data that does most to commend this position is that of Hodinott-Hill et al. (2002) so a fuller discussion of their methodology seems appropriate at this time. In their experiment, subjects wore headphones, through which a sequence of three standard tones (50 ms, 700 Hz, separated by 1000 ms) was presented to the right ear. The fourth tone could be of either higher or lower pitch than these standards, signalling subjects to press one of two buttons. This button press marked the beginning of the variable length comparison period (controlled using a modified binary search procedure). Its end was marked by a standard tone, with a further sequence of three standard tones (separated by 1000 ms) providing the reference periods. Subjects judged whether the comparison period was longer or shorter than the reference periods, and subjective second values were derived. In a second condition, an identical procedure was employed, except that the first tone after the key press (marking the end of the comparison period) and all subsequent tones were

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2 Spatial attention will be treated here as a rather simplified, unitary phenomenon that spans sensory modalities. This simplification is, however, broadly consistent with a great deal of recent experimental evidence (summarised in Driver and Spence, 1999; Eimer, 2001).
presented to the left ear (i.e. shifted hemispaces). Subjective second values were significantly lower in the shift condition than in the control (no shift) condition (825 versus 955 ms, a 130 ms difference).

There are a number of ways to interpret what is occurring in this experiment. The problem is that the timing of the critical event (the shift of spatial attention) can only be approximately inferred from task instructions. Assuming that the conditions were presented in separate blocks (not actually specified in the paper) it seems likely that subjects would choose to shift their attention at some point between the low/high discrimination tone and the first tone after the key press. The most likely sequence of events would be: discrimination tone (right ear) - key press - attention shift - left ear tone. However, other possibilities exist. If subjects did not shift attention to the left ear until the first tone was actually presented there, a prior entry explanation becomes plausible. For brief stimuli like the tones employed in this study, events occurring at an attended location are judged to have occurred before events occurring at an unattended location. The first tone presented in the left ear would therefore be temporally delayed relative to the condition in which no hemispheric attention shift occurred, effectively lengthening the perceived duration of the comparison period and shortening the perceived duration of the first reference period. Whether the magnitude of such an effect could explain the entire 130 ms difference is questionable, but the issue remains problematic.

The attention shift might also have occurred in the period between the discrimination tone and the subject’s two-choice response. It is not clear whether subjects were expected to complete this task in a speeded manner or could prepare themselves fully for the subsequent time estimation task before pressing the appropriate response button. In either case, they might reasonably have shifted attention just before responding, in which case the attention shift might have been used as a cue to begin timing (if the attention shift occurred well before the key press, it is difficult to explain why any difference was obtained between experimental conditions). Regarding the key press, we can only speculate regarding what part of the movement
might have been used as the starting point for time judgements in the absence of any attention shift. Assuming the key did not provide a clear auditory cue (e.g. a click) subjects might have relied on an estimate of the time they sent their command to move (generally judged to have occurred well before a key press is recorded; Haggard and Eimer, 1999; McCloskey, Colebatch, Potter, and Burke, 1983) or their perception of when their movement was actually initiated (again often anticipatory, e.g. Dassonville, 1995). In synchronised tapping tasks, however, when tapping along with a metronome’s clicks, subjects show a consistent bias to tap early (as measured by the time on key contact) leading to the suggestion that they are actually synchronising reafferent feedback from click and tap (Drewing, Hennings, and Aschersleben, 2002; Mueller, Aschersleben, Koch, Freund, and Prinz, 1999). This result might imply that subjects would typically time the interval based on afferent information available slightly after the key is depressed, although if this were the case it is odd that subjective second estimates fell below a second in the no shift condition (a delay in timing onset would require an extended comparison period relative to reference periods). This discussion highlights two points. The first is that the timing task was still subsequent to a movement, even though the movement was made in both conditions (hence the attention shift must have had an additional influence on time estimation). The effect is therefore not necessarily purely attentional, but may result from the interaction between attention and movement. The second is that the movement provided a rather ill-defined starting point for the comparison interval, such that the onset of timing had considerable potential for modification.

Turning now to an account in which attention did not shift until after the key press was made, Hodinott-Hill et al.’s own arousal theory is the only immediately apparent explanation for their results. The diversion of resources required by the attention shift might seem a likely cause, but in fact predicts the opposite effect. The necessity for an “attentional gate” component in the internal clock model is debatable (Lejeune, 1998; Zakay, 2000) but there is general agreement that diversion of resources away from
a timing task lessens the rate of pulse accumulation in some manner. Any diverting task performed during a timed interval would therefore be expected to decrease, not increase, its perceived duration (e.g. Macar, 2002; Zakay, 1998). Similarly, it might be argued that the period of silence was not processed until the required shift of attention was completed. Muesseler and Aschersleben (1998) have proposed a similar explanation of the Fröhlich effect, where the onset of a moving stimulus in mislocalised in the direction of motion (i.e. attention takes time to reach such a sudden onset stimulus and correlates with perception). Here too, we would expect an underestimation of the comparison period (and therefore an increase in the subjective second).

A critical question arising from this discussion is whether Hodinott-Hill et al.'s auditory chronostasis study indexes the same processes as the chronostasis experiments reported here, or depends upon alternative mechanisms. The similarity in effect size found in both cases is suggestive of a joint explanation, but a single arousal-based account of all the relevant data has already been found wanting. Does an account implying backdating to a shift of spatial attention fare any better? In the case of Hodinott-Hill et al.'s data, it might be that the finger movement represents a sufficiently uncertain start point (being both preceded and followed by silence) that a shift of spatial attention occurring just prior to this point would be used in preference. This account would be relatively easy to test by simply having the key press cause a tone to be presented to the right ear (same ear as earlier tones). This event would act as a single preferred start point in both no shift and shift conditions, and help localise the shift of attention to a moment after its occurrence. On the attention backdating account, auditory chronostasis would disappear. On the arousal account, it would remain. An additional condition in which this key-press-triggered tone was presented to the left ear would also be useful, presumably necessitating a shift of attention in the previous period from the high/low discrimination tone to the response.
In the absence of data bearing on this point from the auditory chronostasis paradigm, it is useful to consider the role of attention in the experiments reported in this thesis. The idea that a shift of spatial attention acts as a time marker is consistent with the saccade size dependency data reported in Experiments 1a and 6c. The attention shift might be the oft referred to “pre-motor event” that is used as a time marker. Experiment 1d attempted to address the role of attention by requiring subjects to make an early, deliberate reallocation of attention before their eye movements and found little modulation of chronostasis in this condition. Interpretation is vexed however by the intimate relationship between movement and attention (Rizzolatti, Riggio et al., 1994) and possible differences between mechanisms of endogenous and exogenous attention (Pashler, Johnston, and Ruthruff, 2001). A more telling objection perhaps arises from Experiment 6a (manual chronostasis). In reaching movements where eye position is initially specified but subsequently unconstrained, the eye tends to move before the hand (Prablanc and Martin, 1992) probably reflecting similarly rapid movement specification processes operating upon very different effectors. On a premotor view, we would expect spatial attention to precede the eye movement (and therefore the arm movement) in shifting to the reach target. The eyes travel straight to target, and do not first take in the initial hand position. When preparing a reach to a clearly specified target with eye movements completely unconstrained, subjects would therefore be expected to position both fovea and spatial attention at the target in advance. Experiment 6a differed from this situation because eye position was set and fixation monitored. Nonetheless, it is rather unclear why a shift of spatial attention would occur (rather than simply attending to the target early on). Even if it did (if, for example, subjects were suppressing a planned eye movement to accompany the arm movement, engendering an attention shift, or found it too demanding to maintain attention away from fixation for long periods) it would be expected to occur near the time of arm movement initiation. The magnitude of chronostasis, however, suggested backdating to a point over half way through the movement. It is difficult to fully address
the location of spatial attention without introducing a secondary task of some kind, but intuitively it seems unlikely to account for this data is a straightforward manner. In Experiment 6b, where a shift of spatial attention seems more plausible immediately prior to the temporal judgement (from the reach target back to the coloured window at fixation) little or no chronostasis emerges.

We are faced, then, with the ever-increasing fractionation of the chronostasis phenomenon. It appears necessary to posit rather different hypotheses to account for data from superficially analogous experimental situations. We can, however, attempt to speculate upon boundary conditions necessary to produce chronostasis-like effects. Some degree of uncertainty about the onset time of the stimulus state that is being judged seems necessary, but is in itself insufficient to cause the illusion (Experiment 1b: counter moves to point of fixation). Chronostasis-like phenomena have always arisen following a movement of some kind, so movement may be necessary but not sufficient (Experiment 2a: shifting counter destroys chronostasis; Experiment 6b: reaching to trigger a change of screen colour yield no illusion; Hodinott-Hill et al., 2002). The interaction between movement and shifts of spatial attention may have some part to play, but this linkage may also not be a necessary one (Experiment 1d: early attention shift has no effect on chronostasis; Experiment 6a: reach-dependent chronostasis; Hodinott-Hill et al., 2002). Whether an overarching framework can be found to explain these data (with subtle differences to explain specific instantiations of the illusion) or some experiments will require separate explanations that belie cosmetic similarities remains to be seen.

*Alternative accounts of chronostasis and its possible functional role.* Chronostasis might be an epiphenomenon in one of two senses. It might either arise as a by-product of some process with a clear behavioural goal, or as a by-product of a process that is itself a consequence of other biological needs or constraints. Two of the accounts of chronostasis that
have already been presented provide examples that view the illusion as either one or many degrees removed from a clear functional role. The idea that receptive field shifts for specific groups of neurones permit the rapid or advanced preparation of further movements, but also engender a related shift in perceptual processes, is an example that links the illusion quite closely (but not directly) to a valued behavioural outcome. The arousal account of chronostasis, by contrast, would see the illusion more as an accidental outcome of a quite general process. Arousal is clearly adaptive in its overall physiological effects, but its specific effect on time perception is most naturally seen as a consequence of general physiological constraints to which the timing system is tied (although a specific adaptive account could perhaps be constructed). It is also possible, however, that chronostasis is in itself directly functional. Two such functional accounts are presented here; both are speculative and rather lacking in detail at this stage.

Firstly, might chronostasis relate to the process of action generation and motor learning? Computational accounts of motor control emphasise two kinds of internal model necessary for action. Inverse models take a desired outcome and calculate the manner in which it can be achieved. Forward models take a motor plan and estimate its consequences. Both kinds of model must be built up (learnt) in the course of skill acquisition (Wolpert and Flanagan, 2001; Wolpert, Ghahramani, and Flanagan, 2001). Such learning necessarily depends on the comparison of a movement with its sensory (reafferent) consequences. For the learning of inverse models, the relevant consequence might be a particular movement outcome, such that only behaviourally relevant movement parameters are tightly constrained (Todorov and Jordan, 2002). Reinforcement learning algorithms can generate improvements using only global rewards, rather than deviations from very specific outcomes. For forward models, improvements in model validity must inevitably be more closely tied ongoing reafferent information, because it is this information that is to be predicted. Given that there is a delay between the computations used to generate a movement and the arrival of that movement’s reafferent consequences, how does the
system make the appropriate corrections? Chronostasis might offer a mechanism to aid this process by temporally linking processes of movement specification with their reafferent consequences, giving the illusion a relatively general role. Hence it differs in saccadic and manual paradigms because movement specification is more continuous/ongoing for reaching behaviour. It might be objected that chronostasis is an illusion of conscious awareness, so linking it to motor learning (a phylogenetically ancient process) is questionable. However, the way in which consciousness has emerged from and mirrors basic functions in largely unresolved, and there is ongoing debate regarding how “automatic” motor learning processes are (see e.g. Shanks and Channon, 2002, on the implicit/explicit distinction). The validity of a motor learning account is ultimately an empirical question, and will depend upon 1) demonstrations that the illusion supports motor learning, which is selectively impaired in its absence and 2) demonstrations that the particular reafferent information chronostasis backdates actually matters in the context of motor learning.

A second possible functional explanation relates to the maintenance of object representations over time. As reviewed in Chapter 3, we appear to maintain a limited number of visual objects at any given moment, presumably those that appear behaviourally salient. Keeping track of such objects might alleviate processing delays that would otherwise arise when re-establishing their properties. Recall the discussion of onset uncertainty presented in Chapter 7; the system is presumably interested in the state of represented objects at all times, not merely those times at which it has direct sensory evidence. The state of a particular object property may not always be directly available, however, perhaps because of some interruption or degradation in incoming sensory information. Examples would include visual information during a saccade, colour information when an object is in the periphery, or tactile information when an object is not being contacted. Chronostasis might offer some help here by facilitating the moment to moment linkage of object representations. If we assume that it is difficult to maintain a representation across a temporal gap, for example, then advanced
preparation for a predictable upcoming gap (i.e. one produced by a movement) might alleviate this difficulty.\(^3\) Hence chronostasis reflects a process that seeks out a given object in advance of a perturbation to permit continuous representation of that object (note the similarity to the previously discussed explanation in terms of receptive field remapping). It is not immediately clear, however, why this process results in manual chronostasis for an object that presumably had no prior representation for its tactile property. A second non-exclusive possibility is that in constructing a representational timeline for objects, the system finds value in having accurate past knowledge. The timing of state changes may be valuable in themselves (for example to predict a future periodic state change). As experimenters, we consider that the system is getting it wrong when we observe chronostasis. From the perspective of the system, however, the assumption that a change occurred at the very moment a movement (or attention shift?) provided new sensory evidence is probably not very adaptive. Better to expect another change sooner rather than later. Such an account would of course require considerable elaboration to become a strong theoretical position.

**Relationship with previously reported temporal illusions.** In the course of this thesis, a number of temporal illusions besides chronostasis have been mentioned. As described in Chapter 1, a number of these may relate to arousal-dependent modulation of the pacemaker component of an internal clock (e.g. sounds being judged longer than lights; Wearden, Edwards, Fakhri, and Percival, 1998). Based on the previous discussion, chronostasis does not appear to be another such case, although arousal may have a part to play. Three illusions that do not appear to depend on mechanisms of arousal and might be of relevance to chronostasis are the

\(^3\) In this context, it may be appropriate to mention an earlier assertion that chronostasis might yield the impression of perceptual continuity across saccades by effectively stitching up visual scenes. This may be the case, but it seems likely that this is a consequence of the illusion (which itself might serve some other purpose, like assisting with object representation) rather than a cause. This is because continuous visual consciousness would
time order error (Hellstroem, 1985), Rose and Summers’ (1995) stimulus train illusion and intentional binding (Haggard, Clark, and Kalogeras, 2002). The time order error may play some part in chronostasis experiments, but the inclusion of constant fixation control conditions ensures that the crucial experimental comparisons are unaffected. In the current context, its value is primarily as a possible explanation for depressed subjective second estimates in control conditions. Regarding Rose and Summers’ (1995) results, their finding may again be relevant to the control conditions used here, although the difference in results is far more striking than the overlap. Chronostasis does not depend upon a train of stimuli being presented, whereas their illusion presumably does. The stimulus train illusion must also depend upon the visual context before the train, or the precise nature of the stimuli contained therein (identical and separated by a brief gap) given the failure to replicate it fully in the control conditions employed here. Direct overlap between the two illusions appears limited.

Regarding intentional binding (the shift in the perceived time of both a stimulus and a motor act when they are paired, described briefly in Chapter 6) there are clearly grounds for comparison. In both chronostasis and intentional binding, the consequences of an action appear to be being drawn towards the action itself. However, a number of important differences are also evident, so integration is not easily achieved except perhaps at a quite general level. As the name suggests, intentional binding appears to depend upon the intentional nature of the motor act. Chronostasis emerges even for reactive saccades, movements that rank rather low in terms of intentional control, but it is reasonable to argue that these eye movements clearly “belong” to a subject in a way that the TMS-induced twitches tested by Haggard, Clark, and Kalogeras (2002) do not. More importantly perhaps, intentional binding affects a delayed stimulus delivered contingent upon a motor act, and draws it towards the point of movement generation. It also effects the perceived time of the movement itself. Chronostasis effects the immediate sensory consequence of a movement and appears to draw it not in itself appear to be functional. One difficulty, of course, is that no one really agrees on
backwards within the timecourse of that motor act. The effects therefore look broadly similar, but methodological differences make a clear comparison difficult. A correlation study would be revealing in this respect. One important factor connecting intentional binding, the stimulus train effect and chronostasis, however, is that they all appear to demonstrate the philosophically interesting point that the perception of the timing of an event can be influenced by events occurring after it. In this sense they all tend to bolster Dennett and Kinsbourne’s (1992) position rejecting immediate and persistent on-line conscious awareness of temporal order.

**Relationship with instantaneous time perception.** Following on from the previous philosophical consideration, it is reasonable to object that in the case of chronostasis what has been demonstrated is not the backdating of stimulus onset time but the stretched perception of an interval (reflected in the lengthy discussion of the arousal account). Unfortunately, the attempt to investigate the perceived onset time of the first post-saccadic stimulus relative to other near-instantaneous events was a notable weak link in the experiments reported here (along with the experiments looking at position discrimination following a saccade). There is clearly much scope for better-designed studies exploring this issue, particularly given the possible overlap between the chronostasis results described here and the data relating to temporal order judgements about gaze direction reported by Deubel, Irwin, and Schneider (1999). One particularly intriguing line of inquiry relates to what occurs when chronostasis is broken (as in the target-shift experiments of Chapter 3). Is the saccadic interval still “stitched” such that the pre-saccadic stimulus is now perceived up until the moment the eyes arrive at their new target? The temporal order judgement paradigm might offer answers if, under standard (chronostasis eliciting) conditions, the initial perception of post-saccadic stimulus onset can be shown to arise early relative to some reference point, while the offset of the pre-saccadic

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what function consciousness actually serves in the first place.
stimulus is delayed. A reverse pattern when chronostasis failed would then offer another interesting and provocative result.

Relationship with the internal clock model. The time judgement required in a typical chronostasis experiment must necessarily be considered in the light of models of interval time perception. The possible role of arousal as opposed to early switch closure had already been discussed in some detail. It should be noted, however, that the apparent combination of constant and proportional effects obtained in Experiment 5a might have arisen from other clock components such as the memory stores or the decision process, an issue which the current data cannot clearly resolve. One interesting result reported here is the illusion's differential effect on motor timing and perceptual timing in Experiment 4a. This result is rather unusual in the timing literature, in that it appears to offer quite strong evidence that at least two clocks (one perceptual, one motor) can operate simultaneously and without apparent communication. In this sense, chronostasis does appear to have something to offer regarding our understanding of co-ordinated interval timing processes.

Although discussion has been primarily in terms of the SET internal clock model, the general considerations discussed may reasonably be applied to architectures that vary quite radically from the classic pacemaker-accumulator model. Most of the components evident in SET (e.g. the memory stores, comparator, and switch or related interval marker) appear logically necessary in almost any conceivable timing model (Matell and Meck, 2000). To take one example, Rosenbaum (2002) has proposed a "broadcast" model in which timing is accomplished directly by establishing circular chains of neurones for a given task. The transmission time between neurones can be varied depending on the architecture of a chain, such that almost any interval can be timed repetitively. This simple model can account for scalar timing, a linear psychophysical law and a number of other effects. Although not discussed, an arousal effect could presumably be explained by positing an increase in neural transmission speed. Effectively,
this system replaces the pacemaker accumulator, but it still requires signals to begin and end timing and a decision process of some kind. Hence chronostasis does rather little to help discriminate between individual clock proposals (as opposed to their possible interaction at a higher level) and can be incorporated within a number of frameworks.

Physiological basis of the illusion. The possible links between chronostasis and receptive field shifts has already been discussed in some detail, implicating lateral intraparietal cortex (although similar shifts occur in other sites like the frontal eye fields). As discussed in Chapter 6, the fact that the movement-related signal used to trigger saccadic chronostasis appears to arise quite late in the production of an eye movement (e.g. brainstem burst generator or superior colliculus) is not inconsistent with a role for parietal neurones because efferent information might be projected back to other areas just before movement initiation (Sommer and Wurtz, 2002). Given that all of the experiments reported here were on neurologically normal subjects, and that none incorporated electrophysiological recordings, scanning or TMS-induced virtual lesions, it is clear that any comments about brain sites must be entirely speculative. One possible account for eye movements is that efferent information is passed from the superior colliculus to posterior parietal cortex (perhaps via the frontal eye fields) then projected to prefrontal areas that may attentionally control (Rao, Mayer, and Harrington, 2001) or actually implement (Lewis, 2002) a timing process. This account conforms broadly to one in which the post-saccadic stimulus is predated and the clock begins to run early on. Alternatively, reafferent information from the eyes might reach prefrontal cortex after a movement and affect the decision process. Given that there is currently little consensus about which brain areas implement the various clock functions, further discussion is perhaps best left until relevant data has been gathered.
**Concluding remarks.** Chronostasis is a new illusion of time perception that has already excited controversy. To the extent that it can be characterised, it appears to represent the extension of a newly revealed percept backwards in time following a movement. A number of explanations have been considered and found wanting, although there is clear promise for a more fully developed, possibly hybrid account to emerge in future. The illusion may prove useful in linking previously disparate research traditions (e.g. interval/instantaneous timing, motor learning across effectors, visual short term memory, action planning). What is perhaps most clear from this discussion, however, is that a great number of potentially interesting experiments remain to be carried out.
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Appendix A. The modified binary search algorithm

The modified binary search (MOBS; Tyrrell and Owens, 1988) is an extremely efficient adaptive psychophysical procedure for threshold estimation. Its primary strength is its ability to converge on an estimate very rapidly, while still permitting observers to recover following a lapse of judgement. The MOBS procedure works by maintaining two boundaries and presenting a value midway between them. On each trial, an observer’s response determines whether the value that is currently being tested replaces the low or high boundary. If they respond “lower” then the current value replaces the lower boundary and vice versa. The next value is then selected as the midpoint between the two updated boundaries. A three-value memory is maintained for previous boundary values, such that checks can be implemented to ensure that boundaries can be pushed out again. Specifically, if the same response is made three times in a row (e.g. “lower”, “lower”, “lower”) the algorithm tests the current value of the opposite boundary (the high boundary). A fourth identical response (“lower”) resets this boundary to its previous level. The final estimate is the midpoint value for the two boundaries after two conditions are met. Firstly, a given number of reversals in choice must have occurred (always five for the experiments reported here). Secondly, the difference between the two most recently tested values must be less than an arbitrary value (always 30 ms for the experiments reported here). If the first condition is met but the second is not, two further reversals are required before termination.

One change to the original algorithm employed throughout this thesis is that the initial presentation value was not always the midpoint of the two boundaries. This would typically have resulted in the presentation of a first stimulus duration that was objectively identical to the later comparison stimuli durations at the beginning of each block. Instead, the initial presentation value was randomly generated from a uniform distribution centred upon the midpoint of the initial upper and lower boundaries. The procedure implementing the MOBS was called at the end
of each trial to update the relevant values. It was programmed in Microsoft Visual Basic (V6.0) and is presented here with some explanatory comments (lines preceded by a ' are comments within the programme; italicised text denotes comments that have been added here).

The following code establishes the variables that contain the parameters for a MOBS, and is called at the beginning of a block. This is an example from a typical experiment in which only one MOBS was operating at a time in a given block.

‘initialise MOB variables

    LowBound = 200
    HighBound = 1800

    Reversals = 0
    Responses(4) = 0
    ExitRun = False

    For j = 1 To 3
        LowBoundary(j) = LowBound
        HighBoundary(j) = HighBound
        Responses(j) = 0
        WaitTime(j) = 0
    Next

    Randomize

    WaitTime(3) = Round(((LowBound + HighBound) / 2) * ((0.8 * Rnd) + 0.6))

Lowbound and highbound are the designated outer limits of the search for this experiment. Reversals is the number of times the subject has reversed their choice. ExitRun is used to tell the programme when it should stop generating trials and end the block. Responses is an array with four values, containing the current and previous three responses made by the subject (0 = no response). LowBoundary and HighBoundary are arrays with three values. They will contain the value of the current low and high boundaries.
as well as the two previous values for each boundary, but are initially set at the search's designated limits. WaitTime is a three element array that holds the value presented on the current trial (WaitTime(3)) and the previous two trials. The initial presentation value is randomly generated with a distribution that is symmetrical around the midpoint of the search's designated limits.

The following code calls the MOBS procedure (called ModifiedBinarySearch) following a successful trial:

If Saccaded = True Then

    'do the MOB thing.

    ModifiedBinarySearch Judgement, Responses(), HighBoundary(), _
    LowBoundary(), WaitTime(), _
    Reversals, MinStep, ExitRun, _
    BlockResult, LowBound, HighBound

End If

In addition to the previously defined variables, three further variables are passed to the ModifiedBinarySearch procedure. Judgement is the subject's response on the trial that has just been completed (1 = less than, 2 = greater than). MinStep is a constant holding the minimum difference between the previous two presentation values that will be accepted when a search terminates (here it has the value 30). BlockResult will hold the final threshold value when the block terminates. Up until this point its value is 0.

The following code implements the updating of MOBS parameters on each trial and decides whether the block is complete. The variables that were passed in the previous code segment are renamed in the procedure's definition line (Public Sub ...). Hence ThisDecision = Judgement, R = Responses and so forth.

Public Sub ModifiedBinarySearch(ThisDecision As Integer, _
R() As Integer, h() As Single, l() As Single, Search() As Single, _
Crossings As Integer, MinShift As Single, ExitCondition As Boolean, _
Outcome As Single, LB As Integer, UB As Integer)

'implements a modified binary search iteration, returning
'exitcondition = true to terminate

R(1) = R(2) 'this section places the most recent response
R(2) = R(3) 'in R(4) and shifts the other responses back
R(3) = R(4) 'one place
R(4) = ThisDecision

If R(1) = 1 And R(2) = 1 And _
R(3) = 1 And R(4) = 1 Then 'checks to see if the last four
'responses were all "lower"

   For j = 1 To 3
      R(j) = 0 'if so, resets the response memory
   Next

   h(3) = h(2) 'then shifts the upper bound memory values
   h(2) = h(1) 'forward to reinstate the previous value
   h(1) = UB

   Search(1) = Search(2) 'the memory for previous values is
   Search(2) = Search(3) 'updated and a new value created for
   Search(3) = (l(3) + h(3)) / 2 'presentation next trial

ElseIf R(1) = 2 And R(2) = 2 And _
R(3) = 2 And R(4) = 2 Then

   For j = 1 To 3
      R(j) = 0 'this process is identical but opposite
      Next 'four responses were all "higher"

   l(3) = l(2)
   l(2) = l(1)
   l(1) = LB

   Search(1) = Search(2)
   Search(2) = Search(3)
   Search(3) = (l(3) + h(3)) / 2

ElseIf R(2) = 1 And _
R(3) = 1 And R(4) = 1 Then 'this time, checking to see if just
'the last three responses were
    Search(1) = Search(2) "lower". If so, the next value
    Search(2) = Search(3) 'checked will be the current
    Search(3) = h(3) 'high boundary.

ElseIf R(2) = 2 And _
    R(3) = 2 And R(4) = 2 Then 'same check, but for three "high" _
    'responses
        Search(1) = Search(2) _
        Search(2) = Search(3) _
        Search(3) = l(3) _

ElseIf R(4) = 1 Then 'if the last response was "lower"
    l(1) = l(2) _
    l(2) = l(3) 'shuffle the low boundary memory back
    l(3) = Search(3) 'and replace its current value with that
        'just tested
        Search(1) = Search(2) _
        Search(2) = Search(3) _
        Search(3) = (l(3) + h(3))/2 'then update the memory for previous
            'presentations and select a new
            'value

ElseIf R(4) = 2 Then
    h(1) = h(2) 'this is the opposite process for
    h(2) = h(3) 'a "higher" response
    h(3) = Search(3)
        Search(1) = Search(2) _
        Search(2) = Search(3) _
        Search(3) = (l(3) + h(3))/2

End If

If R(4) <> R(3) And _
    R(3) <> 0 Then Crossings = Crossings + 1 'add one to the reversal
    'counter if appropriate
    'exit condition test (+ outcome =)
If Crossings >= NoOfCrossings Then
    If Search(3) - Search(2) < MinShift Then _
        ExitCondition = True 'if both conditions are met,
        Outcome = (l(3) + h(3))/2 'end the block and calculate
            'a block value
    Else
        Crossings = Crossings - 2 'if only the reversal condition
End If

's is met, lower the reversal
'counter and continue with the
'block

End If

End Sub
Appendix B. Timing issues in Visual Basic

Microsoft visual basic is a language that permits relatively rapid development times for windows applications. Its basic library of objects and functions are not, however, particularly well suited to the needs of the psychophysical researcher. Luckily, its scope has increased dramatically in recent versions, with much improved access to the function libraries that comprise the windows 32-bit application programmer's interface (API). Here, a number of problems relevant to achieving precise timing are discussed, along with the solutions employed when programming for the series of experiments described in this thesis. Brief reference will also be made to the functions contained within the National Instruments NIDAQ32.DLL file, which is shipped with the DAQcard-1200 analogue to digital input/output card used in all experiments as an interface between the PC and experimental apparatus. Technical information has been derived primarily from the Microsoft web site, particularly the MSDN online library, and Appleman (1997). Trial and error has also proved an invaluable resource.

Platform issues. Although they have obvious benefits in terms of being user friendly, recent versions of the MS windows operating system are quite different from DOS in one very important respect. Programmes running under DOS have complete access to the central processing unit, which means they will execute line by line until completed, at which point another programme gains control. Windows is different, being an architecture designed for multitasking. For more recent versions in particular, this means that as a programmer it is impossible to ensure that a programme executes in its entirety before other programmes are allowed to use the CPU. The operating system retains control of CPU resources and will always implement some degree of “pre-emptive” multitasking by suspending programme execution as it sees fit to allow system operations to occur and other programmes to share resources. When running a programme with time
critical operations, it is therefore well worth remembering to close all other applications. Windows will still take control of the CPU (e.g. to check for keyboard and mouse messages) but its interference more limited when other applications are not running. Enforced multitasking is a general problem for all windows applications, whether programmed in visual basic or a lower level language like C++. Consequently, some researchers remain true to DOS-based systems and some manufacturers offer windows development environments that permit programmes to subsequently be compiled for specialised real-time operating systems. A partial solution when working within windows is to assign a high processing priority to the experimental application, which can be achieved in visual basic by first including the following constants and API links:

'process (programme) priorities
Public Const NORMAL_PRIORITY_CLASS = &H20
Public Const REALTIME_PRIORITY_CLASS = &H100
Public Const HIGH_PRIORITY_CLASS = &H80

Public Declare Function GetCurrentProcess Lib "kernel32" () As Long
Public Declare Function SetPriorityClass Lib "kernel32" (ByVal hProcess As Long, ByVal dwPriorityClass As Long) As Long

And then using code such as that shown in the following example:

Handle = GetCurrentProcess()
Temp = SetPriorityClass(Handle, HIGH_PRIORITY_CLASS)
If Temp = 0 Then MsgBox "Problem raising process priority class"

Here and in later examples, Handle and Temp are long integers. Note that the HIGH_PRIORITY_CLASS level is the highest setting available under visual basic, whereas C programmers can also set the priority level to the superior REALTIME_PRIORITY_CLASS using the same API call. Nonetheless, performance is generally acceptable. Regular time logging across trials was implemented in the experiments reported here (written to a special timing file) and generally showed only very sporadic pauses in programme execution that rarely exceeded 15 ms.
On the subject of platform issues, it should perhaps be noted that visual basic suffers an undocumented problem under Windows 2000 when commands to print graphics to screen occur in the context of precisely timed intervals (see next section). Graphics commands do not work properly under these circumstances. A solution is to ensure that graphics commands (including CLS) are followed by a windows paint message sent to the appropriate window. The relevant constants and API link should be declared:

Public Const WM_PAINT = &HF

Public Declare Function SendMessage Lib "user32" _
    Alias "SendMessageA" (ByVal hwnd As Long, _
    ByVal wMsg As Long, ByVal wParam As Long, _
    lParam As Any) As Long

And the message sent as follows:

'windows paint message to ensure update
Temp = SendMessage(WinHandle, WM_PAINT, 0, 0)

Here WinHandle is the handle of the relevant window. Note that this approach works reliably despite the fact that Microsoft’s own documentation states that paint messages should never be sent within visual basic programmes.

Achieving precise timing. Visual basic is set up to be an event driven language. Hence typical applications will spend a considerable amount of time waiting for user input, only performing key operations when prompted to do so. This approach contrasts with DOS-based programming languages, where the programmer effectively produces a continuous script for the application to follow at all times and defines the points at which the user can interact. For experimental programming, this is perhaps a more natural approach, although a combination of both methods can save time when producing applications. The only timing capabilities offered within visual
in the timer control. In its basic functioning, the timer control can be set to execute a given chunk of code every time a given interval passes; because it can be turned on or off at any time, a single interval can be timed in this manner. In the meantime, the system is free to respond to the user. Unfortunately, visual basic’s timer control is relatively inaccurate by the standards of psychophysical experiments; experimenting with an oscilloscope shows that it is regularly wrong by upwards of 30 ms for a given interval, clearly unacceptable as an error arising on almost every trial. Two approaches have been taken here in overcoming this problem, both relying on functions contained in the windows multimedia function library. The relevant API links, types and constants are:

```
Type TIMECAPS
    wPeriodMin As Long
    wPeriodMax As Long
End Type

'timing function constants
Public Const TIME_ONESHOT = 0 'program timer for single event
Public Const TIME_PERIODIC = 1  'program for continuous periodic 'event

Public Declare Function timeBeginPeriod Lib "winmm.dll" (ByVal uPeriod As Long) As Long
Public Declare Function timeEndPeriod Lib "winmm.dll" (ByVal uPeriod As Long) As Long
Public Declare Function timeGetTime Lib "winmm.dll" () As Long
Public Declare Function timeSetEvent Lib "winmm.dll" (ByVal uDelay As Long, ByVal uResolution As Long, ByVal IpFunction As Long, ByVal dwUser As Long, ByVal uFlags As Long) As Long
Public Declare Function timeKillEvent Lib "winmm.dll" (ByVal uID As Long) As Long
Public Declare Function timeGetDevCaps Lib "winmm.dll" (IpTimeCaps As TIMECAPS, ByVal uSize As Long) As Long
```

Before these functions can be used, the timer’s resolution must be set to 1 ms or the lowest resolution permitted by the operating system. For example:

```
Temp = timeGetDevCaps(Resolution, 8)
```
MsgBox "Timing resolution...Max = ", 
& Resolution.wPeriodMax & ", Min = ", 
& Resolution.wPeriodMin & " ms. Minimum resolution will be instantiated.", 
vbOKOnly, "Timer info"

Temp = timeBeginPeriod(Resolution.wPeriodMin)

Here Resolution is a variable of the TIMECAPS type defined above. It is also necessary to release the timers before the programme exits:

Temp = timeEndPeriod(Resolution.wPeriodMin)

Two approaches can now be taken to timing programme execution. The DOS-like approach uses the function:

Tvar1 = timeGetTime

This retrieves the system time in ms at any given moment, where Tvar1 is a long integer. The function can be employed within loops to yield precise timing. The alternative event-driven approach is to use the callback function:

'stops execution for 500ms (sets a timer to callback the next function...) 
Temp = timeSetEvent(500, Resolution.wPeriodMin, _ 
AddressOf AllTrial3b, 0, TIME_ONESHOT)

Which automatically calls the following (programmer-defined) function after the specified interval while allowing other operations to continue in the mean time:

Public Function AllTrial3b(ByVal uID As Long, ByVal a As Long, _
ByVal dwUser As Long, ByVal b As Long, ByVal c As Long) As Long

'code here
Temp = timeKillEvent(uID)

End Function

Both approaches are millisecond accurate under all recent windows operating systems. Unfortunately, programmes employing timeSetEvent only appear to run successfully within the visual basic programming environment, so compiled .exe files cannot be used. Any resulting decrement in execution speed appears negligible however.

Synchronous/Asynchronous data acquisition. National Instruments software provides functions for single shot, synchronous and asynchronous data acquisition and output. Synchronous operations are rarely suitable because they occupy the CPU, which means that no other programme commands are executed until the specified number of samples have been acquired or outputted. Single shot functions can be usefully combined with the timeGetTime function in loops to achieve sampling at a given rate while both permitting ongoing use of incoming sampled values and allowing other timed operations to be executed during acquisition. A weakness is that other lengthy operations within the programme as well as background system operations (e.g. multitasking) can lead to a non-constant sampling rate. Asynchronous calls, by contrast, operate in the background and allow other timed processes to occur, making them ideal in combination with an event driven approach to timing. Continuous on-line polling of values can be problematic (e.g. for screen display) given that such an operation requires a double-buffered input/transfer process that imposes a delay. However, if only particular events are of immediate interest, callback functions are available that trigger a named function to execute when a pre-specified event occurs (e.g. when an eye movement signal crosses a threshold in the appropriate direction). Within visual basic, National Instruments have created a number of controls that allow triggering operations to be achieved in a relatively straightforward manner. Examples can be found in their support files.
**Screen timing.** A common problem for experiments using visual stimuli is the variability in stimulus onset times caused by the limited refresh rate of monitors. In general, an interval can only be timed precisely if it begins and ends on a multiple of the screen refresh duration (typically 16.66 ms for the experiments reported here). Variability was inevitable in the current experiments, which used a range of stimulus durations, although such effects were equivalent across conditions. Precise synchronisation of events with screen refresh can be achieved in visual basic, however, using Microsoft DirectX. DirectX provides a function library designed primarily for multimedia applications requiring complex graphics and music (e.g. games design). Developer’s and run-time versions are available for installation from the Microsoft website, and the latter is included as standard on newer Microsoft operating systems. The following code permits access to screen refresh timing under the most recent version (DirectX v8.0/8.1), although it is actually rather more cumbersome than under version 7.0. The relevant version’s type library must be included by selecting “references” from the “project” menu in the visual basic programming environment before DirectX code can be run. Initially, the following variables must be declared:

```
'DIRECT X8 VARIABLES

Public DX8 As New DirectX8
'draw
Public D3D As Direct3D8
Public D3DDevice As Direct3DDevice8
Public D3DVertexBuffer As Direct3DVertexBuffer8
Public DisplayMode As D3DDISPLAYMODE
Public PresentationParameters As D3DPRESENT_PARAMETERS
Public VertexSizeInBytes As Long
Public RefreshInfo As D3DRASTER_STATUS
```

The next section of code sets up the display so that DirectX can be employed. Note that while DirectX provides excellent capabilities for 3D animation, using it to generate simple 2D stimuli is rather like taking a
sledgehammer to a walnut. For the experiments reported here, windows graphics device interface (GDI) commands were used, as they offer improved speed and flexibility relative to visual basic’s own graphics commands.

On Local Error Resume Next

Set D3D = DX8.Direct3DCreate()

If Err.Number <> 0 Then

    MsgBox "Unable to start Direct3D!"
End

End If

'gets details of the default adapter display mode (Refresh, size etc.)
D3D.GetAdapterDisplayMode D3DADAPTER_DEFAULT, _
DisplayMode

If Err.Number <> 0 Then

    MsgBox "Error number " & Err.Number & ": " & Err.Description
End

End If

'establishes some parameters for creating a new display
'device
'windowed mode
PresentationParameters.Windowed = 1
'copy from backbuffer, not swapping, synchronised so that
'vertical raster is elsewhere if poss
PresentationParameters.SwapEffect = _
D3DSWAPEFFECT_COPY_VSYNC
'default adapter display format
PresentationParameters.BackBufferFormat = DisplayMode.Format

'create the d3d device object to actually draw with
Set D3DDevice = D3D.CreateDevice(D3DADAPTER_DEFAULT, _
D3DDEVTYPE_HAL, WinHandle, _
D3DCREATE_SOFTWARE_VERTEXPROCESSING, _
PresentationParameters)

If Err.Number <> 0 Then
MsgBox "Error number " & Err.Number & ": " & Err.Description
End

End If

The following loop can now be employed to hold up a programme's execution until the monitor is ready to begin drawing the screen anew from the top left:

'hold up until next screen refresh
Do

     RefreshInfo = D3DDevice.GetRasterStatus
Loop Until RefreshInfo.InVBLANK = 1

Summary. The functionality offered within visual basic itself make the language very convenient for programming attractive windows applications like those required in a typical workplace, but virtually useless when the desired outcome is the precise control of psychophysical experiments. However, shopping around and incorporating a few API functions can yield results that are comparable to those available using C++. It should be noted, though, that these functions were originally designed for C++ programmers and the translation process is not always an easy one. It is perhaps questionable whether the simplicity of getting started with visual basic makes up for the time wasted wading through the relevant technical notes when lower level control is desired.