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Taking a Long Look at Action and Time Perception

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Everyone has probably experienced chronostasis, an illusion of time that can cause a clock's second hand to appear to stand still during an eye movement. Though the illusion was initially thought to reflect a mechanism for preserving perceptual continuity during eye movements, an alternative hypothesis has been advanced that overestimation of time might be a general effect of any action. Contrary to both of these hypotheses, the experiments reported here suggest that distortions of time perception related to an eye movement are not distinct from temporal distortions for other kinds of responses. Moreover, voluntary action is neither necessary nor sufficient for overestimation effects. These results lead to a new interpretation of chronostasis based on the role of attention and memory in time estimation.

Keywords: time perception, action, attention, memory

The idea that perception guides action is self-evident. The opposite assertion, that action can guide perception, is less obvious, although research in recent years has strongly supported it. It has become increasingly clear that perception and action are not isolated stages of processing but are richly interconnected systems that work together to produce coherent, goal-directed behavior. Linking actions to their sensory effects may be an important element not only of motor learning (e.g., Blakemore, Frith, & Wolpert, 2001) but also of perceptual learning (Hommel, Müsseler, Ascherleben, & Prinz, 2001). The relationship between action and perception is particularly apparent for eye movements, for which the perceptual consequences of actions are immediate: When the eyes move, the entire visual field slides across the retina. Correlating the execution of eye movements with their immediate sensory consequences is fundamental for maintaining a seamless representation of the visual world.

Several studies have addressed the problem of how perceptual unity is maintained in the face of global shifts in retinal positions that occur each time the eyes move. Until recently, the primary focus has been on changes in the form and location of items in the environment. For instance, evidence suggests that the visual field compresses toward the goal of a saccade, starting about 50–100 ms before a saccade is executed (Morrone, Ross, & Burr, 1997; Ross, Morrone, & Burr, 1997). The source of this compression effect may be a signal sent from the oculomotor nuclei to the visual cortex to enable anticipation of, and compensation for, visual movement across the retina as it is occurring (e.g., Sommer & Wurtz, 2006). In a recent study, distortions during saccades were also proposed to arise in the domain of time perception. Yarrow, Haggard, Heal, Brown, & Rothwell (2001) reported that the duration of a visual stimulus is systematically overestimated if it appears during the time that the eyes are in motion. They interpreted this overestimation as evidence of a mechanism for preserving cross-saccadic perceptual continuity of visual events. Their intuitively appealing suggestion was that the percept of the saccade goal fills in across the duration of the eye movement in order to maintain a smooth and continuous construction of visual reality out of what is actually a series of short glimpses interspersed with the jerking, global motion associated with saccadic eye movements. The term *chronostasis* reflects this notion that time appears to freeze during saccades.

This formulation of the chronostasis phenomenon has failed, however, to accommodate recent findings that time overestimations occur for events that are not visual and for responses that are not oculomotor. That is, when the methodology of (Yarrow et al. (2001) was adapted to other situations, observers were found to overestimate the duration of both tactile events (Yarrow & Rothwell, 2003) and auditory events (Alexander, Thilo, Cowey, & Walsh, 2005; Hodinott-Hill, Thilo, Cowey, & Walsh, 2002). Visual events were similarly found to be overestimated when they were triggered by verbal responses and by manual keypress responses (Park, Schlag-Rey, & Schlag, 2003). These interesting findings have led to two additional hypotheses about the source of the chronostasis effect: first, chronostasis has been suggested to occur because the onset of the event is linked back in time to the action that is perceived to have triggered it (Park et al., 2003; Yarrow and Rothwell, 2003). This hypothesis converges with other evidence of temporal binding between voluntary action and perceptual events (Haggard, Clark, & Kalogeras, 2002). It is also consistent with recent theories of action and perception, such as the theory of event coding (Hommel et al., 2001), that suggest perception is shaped by the consequences of voluntary actions. A second, related hypothesis (Alexander et al., 2005; Hodinott-Hill et al., 2002) is that action increases arousal, which in turn increases perceived duration by increasing the rate of the internal clock that supports time estimation (e.g., Treisman, 1963).

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A challenge to chronostasis has also come from a recent demonstration that time, like space, is compressed during a saccade. Morrone, Ross, and Burr (2005) showed that temporal intervals are underestimated and sensitivity to temporal order decreased around the time of a saccade. This finding seems to be in direct conflict with the observation that intervening saccades inflate judgments of time intervals. Morrone et al. (2005) suggested that the phenomenon of temporal compression that they observed is specific to saccades, whereas chronostasis may represent a more general effect of attention and movement planning.

Although the principle of parsimony would prescribe acceptance of a unitary explanation of all temporal overestimation effects of concurrent actions, Yarrow and Rothwell (2003) have argued that the chronostasis effect that results from saccades is distinct from the duration overestimation that results from other kinds of actions. In their original study (Yarrow et al., 2001), when subjects made saccades of two different distances, the duration of the saccade mapped almost perfectly to the magnitude of the illusion, forming the basis for the proposal that perception fills in across the duration of the eye movement. This key finding suggests that the chronostasis effect resulting from eye movements is distinct from the overestimation resulting from other kinds of voluntary actions. In support of this distinction, Yarrow & Rothwell (2003) reported in a recent study using tactile stimulators that the scaling effect that had occurred for eye movements did not occur for reaching responses.

In Experiments 1 and 2 of the present study, we explored temporal perception following eye movements, and the results of these experiments suggest that the scaling effect is an artifact of the methodology used by previous experiments. We also directly compared the effect that eye movements and manual keypress responses have on time judgments and found that both have significant, but equivalent, effects[1]. Based on these past and present findings, we might conclude that chronostasis following eye movements is a subtype of a more general distortion of time perception around the execution of actions and is consistent with theories that emphasize links between actions and their perceivable consequences (e.g., Hommel et al., 2001). However, in both Experiments 2 and 3, we observed that a voluntary action is not necessary to produce a chronostasis-like effect. Instead, we found that the duration of the first digit was overestimated even when it was not triggered by a saccade or a button-press response.

In Experiments 4–6 we explored this general overestimation phenomenon with the goal of addressing two issues: what privileged role, if any, is placed on the stimulus that occupies the first position in a series of events and the extent, if any, to which this position effect can be attributed to the temporal binding of an event to a preceding response. The results of these experiments show that an overestimation of the duration of the first digit in the sequence only occurs among relatively unpracticed subjects and that a voluntary action is neither necessary nor sufficient for these overestimations of duration to occur. The findings lead us to reject the idea that an action itself can distort perceived duration and to propose alternative explanations for the patterns of time estimation observed in the present study and in previous investigations.

Experiment 1: Perception of Events During a Saccade

This experiment examined whether duration overestimation following saccades is unique compared to other voluntary actions. The assertion that saccades and other actions have unique effects rests on Yarrow et al.'s (2001) finding that the magnitude of the chronostasis effect scales with the size of an eye movement. In their study, the initiation of a saccade to the counter triggered a 0 to change to a 1. The number 1 was presented for a variable amount of time before the counter changed to the numbers 2, 3, and 4, with each of these ensuing digits lasting 1 s. The important measure was the duration for which the digit 1 had to be presented in order to be perceived by a subject as lasting for 1 s (hereafter termed a *subjective second*). In calculating this "subjective-second" value, even though the appearance of the digit 1 was triggered by the onset of the saccade, time estimates were "corrected post hoc to match the time that the '1' was on the screen *after target foveation*" (p. 305, Yarrow et al., 2001, emphasis added). This means that the investigators subtracted the length of time that the subject's eyes had been in motion from the subject's subjective-second values. For example, if a subject judged the number 1 as lasting 1 s when it was presented for 950 ms, but it took 100 ms from the time when counter was triggered for the eyes to arrive at the counter, the authors would record the subject's 1-s estimate as 850 ms. Because larger eye movements take longer to execute, the larger the saccade, the larger the value that Yarrow et al. subtracted.

The assumption underlying this correction of a subject's time estimate was that observers were blind to visual events during a saccade; and, hence, they were unaware that the visual display had changed from a 0 to a 1 until their eyes landed on the 1. This assumption led Yarrow et al. (2001) to assert that the actual duration of the 1 should be timed not from when the counter actually changed to a 1 but from when the eyes landed on the 1. The problem with this correction is that the assumption on which it is grounded is probably false. It is well established that people are able to perceive the identity of visual stimuli during a saccade (e.g., see Ross, Morrone, Goldberg, & Burr, 2001; Watanabe, Noritake, Maeda, Tachi, & Nashida, 2005). If the change to the counter's identity was perceived by the observers in the Yarrow et al. study, subtracting saccade durations from time estimates would artificially inflate the magnitude of the illusion. As noted above, because larger saccades have longer durations, Yarrow et al.'s subtraction of the duration of a subject's saccade from the estimate the subject provided would create the erroneous result that the chronostasis effect scales systematically with the length of the saccade. The same adjustment was applied to subject estimates in two more recent articles (Yarrow et al., 2003; Yarrow, Johnson, Haggard, & Rothwell, 2004), making them subject to the same concern.

Experiment 1 tested whether subjects can or cannot perceive a display change during a saccade in conditions designed to match those of the original Yarrow et al. (2001) study. If subjects can perceive visual events that occur at the counter location during a

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[1] Only one previous study directly compared the chronostasis effects for saccadic and manual responses (Park, Schlag-Rey, & Schlag, 2003), and the authors observed a numerically larger chronostasis effect for saccades. However, the result was based on the observations from just two observers and no statistical comparison between the two response conditions was made. It is also not clear whether Park et al. adjusted subject estimates in the same manner as Yarrow et al. (2001).

saccade, it follows that Yarrow et al.'s correction of duration estimations is questionable. Without this correction, there is no evidence that the chronostasis effect scales with saccade duration and, hence, no evidence that the chronostasis effect for saccades is distinct from the chronostasis effect that results from other voluntary actions.

Method

Six participants (including the three authors) viewed the display from a chin rest situated 57 cm from a 16 in., 80 Hz monitor. Eye movements were recorded using an EyeLink eye monitor, producing an estimate of left eye position every 4 ms. The sequence of events in a trial is illustrated in Figure 1. Each trial began with a black fixation point 12.5° to the left of the center of a white screen and a black digit 0 (in sans serif, 48-point type) positioned 12.5° to the right of the center. A rightward saccade from the fixation point to the 0 triggered the 0 to become either an x or a + when the eyes had traveled one-fifth of the distance between them. The x/+ was presented for either 25 or 37.5 ms, depending on what stage of the monitor's screen refresh process the eyes passed the one-fifth point. The majority of the time the stimulus was presented for 25 ms, but occasionally it would be presented for 37.5 ms. At this point, the x/+ stimulus became a 1. After 1,000 ms, the 1 was removed, and participants then indicated whether they saw an x or a + during the saccade. The average duration of a 25° saccade in this experiment was 75.1 ms (with a standard deviation of 6.7), ensuring that the 1 was always present by the time the eyes arrived at the counter location. Participants practiced the task until they were comfortable with it and then completed 24 test trials.

Results and Discussion

Discrimination judgments of the x/+ stimulus were well above chance (81.3% correct, with the accuracy of individual subjects ranging from 66.7 to 95.8% correct, $\chi^2(5) = 32.15$, $p < .001$, demonstrating that detection and identification of a brief stimulus during a saccade is indeed possible. The important implication of this finding is that adjusting subject estimates to account for saccade duration is neither necessary nor justified. It follows that performing the subtraction not only inflates the magnitude of the chronostasis effect but also creates the false impression that the size of the chronostasis effect scales with the size and length of an eye movement. In Yarrow et al.'s (2001) experiment, subject's time estimates were corrected after saccades of 22° and 55° to "match the time that the '1' was on the screen after target foveation" (p. 305). According to a personal communication from the authors (K. Yarrow and P. Haggard, April 1, 2005), an average of 57 ms was subtracted from time estimates in the short saccade condition, and an average of 115 ms was subtracted in the long saccade condition, for a difference of 58 ms. After correction, Yarrow et al. reported a 69-ms difference between saccade distance conditions, which they took as evidence that the magnitude of the illusion depends on the distance of the saccade. However, without any

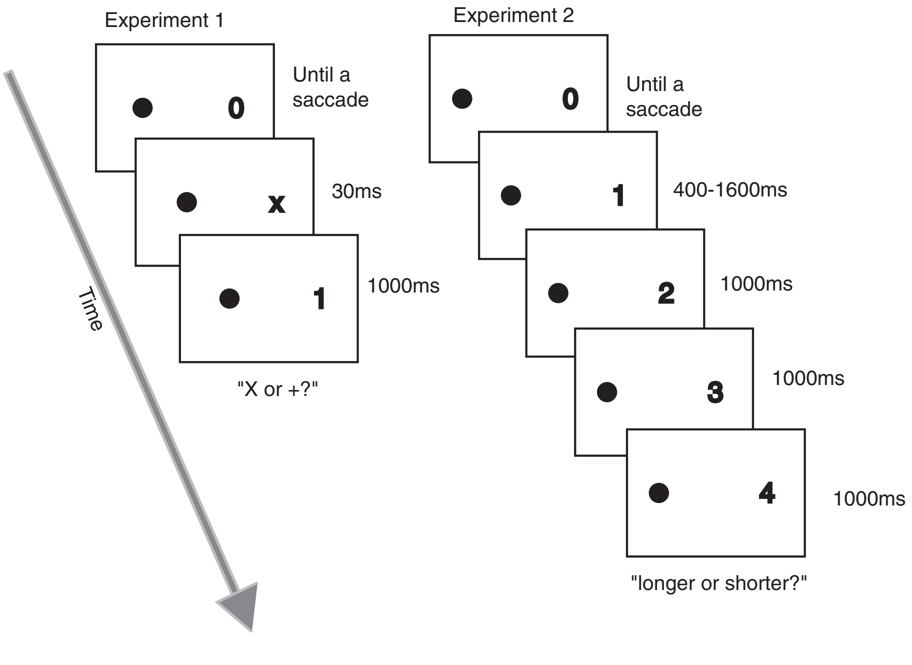

Figure 1. The sequence of events for Experiment 1 and the saccade condition of Experiment 2. In Experiment 1, participants executed a rightward saccade to the digit 0. When the eyes passed one-fifth of the distance, the 0 briefly became either a + or an x and then became a 1 for 1 s. Participants indicated whether a + or an x had been displayed. In Experiment 2, a saccade triggered the change of the 0 to a 1, which remained for 400–1,600 ms (according to the modified binary search procedure). It then was replaced by a 2, 3, and 4, each for 1 s. Participants indicated whether the duration of the 1 was longer or shorter than the subsequent digits.

adjustment by Yarrow et al., the actual subjective-second values between the two conditions would have been much closer, with a difference of 11 ms, and the claim that the magnitude of the illusion scales with the size of the saccade is seriously undermined.[2]

In a control experiment, Yarrow et al. (2001) defended their adjustment of subject estimates by comparing the magnitude of the chronostasis effect when the appearance of the first digit occurred early in the saccade (at one-fifth of the distance between the fixation point and the counter) versus when it was triggered later in the saccade (at four-fifths of the distance). They argued that, if subjects were able to detect the appearance of the first digit, the chronostasis effect should be larger for the early condition, in which the first digit was on for a longer period of time before the eyes reached it. This manipulation did result in a trend towards larger effects in the early condition, but it failed to achieve statistical significance. Based on this null result, Yarrow et al. argued that their subjects were not sensitive to changes in the stimulus. Of course, failure to reject the null hypothesis is not positive evidence, especially given the highly variable nature of their data, as well as the ample literature indicating that people are able to report on visual events during their saccade (e.g., Ross et al., 2001; Watanabe et al., 2005). In any case, the discrimination task used in the present experiment provided a direct test and positive evidence in favor of the conclusion that reliable perception of events at the counter location occurs during saccades.

Experiment 2: Time Perception Following Saccadic and Keypress Responses

The key piece of evidence suggesting that the chronostasis effect following an eye movement was distinct from the overestimation effect following other kinds of voluntary actions was that the chronostasis illusion scaled with the duration of eye movements (Yarrow et al., 2001). In Experiment 1, we found that Yarrow et al. were incorrect in assuming that subjects were blind to a change in the counter during an eye movement and, hence, unjustified in performing the subtraction that created the appearance of a scaling effect. It is, thus, quite possible that the chronostasis effect for eye movements is not unique. In Experiment 2, we compared subjective durations of the first digit following eye movements and keypress responses. We included a condition in which the sequence was triggered without a voluntary action to measure the perception of the first-digit duration in the absence of any effects of voluntary action. In this condition, the first digit appeared 2,000–3,000 ms after the response to the previous trial. A long gap and an unpredictable temporal relationship should weaken binding of action to the change in the visual display.

Method

We replicated Yarrow et al.'s (2001) procedure for eye movements as closely as possible, with the exception that we did not apply their correction in the eye movement condition. The initial display was the same as in Experiment 1 (see Figure 1). Twelve participants executed a 25° rightward saccade from the fixation point to the 0, which triggered the 0 to become a 1 when the eyes had traveled one-fifth of the distance between them. The 1 remained present for a variable amount of time (between 400–1,600 ms) and then was replaced by a 2, then a 3, and then a 4, each of which remained for 1,000 ms. Participants judged whether the duration of the 1 was longer (by pressing the L key) or shorter (by pressing the S key) than the subsequent digits. The duration of the 1 on the following trial was then adjusted based on this response, according to the modified binary search (MOBS) procedure (Tyrell & Owens, 1988), eventually homing in on a duration of the 1 that was subjectively equal to the rest of the digits. In light of our findings in Experiment 1, and hence unlike Yarrow et al. (2001), we did not correct subjective-second values according to the time the eyes were moving. There were two additional conditions: (a) a condition in which the counter (now presented at the center of the display) was triggered when the subject pressed the spacebar, and (b) a condition in which the central counter was triggered after a random intertrial interval of 2,000–3,000 ms. Four estimates of a subjective second were collected per condition for each subject. Subjects were also administered a brief questionnaire following the experiment to ensure that they understood and followed instructions. If, for any given subject, two estimate values under the same conditions had a difference of more than 1 s, that subject was removed from the analysis. Two subjects were removed from further analysis based on this criterion but were replaced by new subjects to maintain counterbalancing.

Results and Discussion

A within-subjects analysis of variance (ANOVA) comparing all three conditions (saccade, manual, and no action) was significant $F(2, 22) = 3.50$, $p < .05$. Post hoc comparisons revealed that the saccade condition produced subjective-second values that were significantly less than the no-action condition, replicating the chronostasis effect (the 98.63 ms difference exceeded the Tukey HSD of 97.96). No other comparisons exceeded the cutoff. Given that the no-action condition is used as a baseline both in this experiment and in others, it is also important to compare subjective-second values produced in this condition to an actual second. Subjective-second values in the no-action condition were 85.51 ms less an actual second, one-group $t(11) = 1.98$, $p < .1$, suggesting that subjects overestimate the duration of the first digit to some degree even when no action is performed. This suggests that the baseline itself is susceptible to overestimation; and, therefore, a comparison of the saccade and manual subjective-second values themselves to an actual second may be a more informative analysis. One-group t tests reveal that both the saccade, $t(11) = 4.04$, $p < .01$, and the keypress, $t(11) = 2.57$, $p < .05$, conditions

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[2] It should be noted that Yarrow et al. (2001) used a duration-judgment task and our experiment required a form discrimination. One possible objection to our conclusion is that perhaps subjects are blind to the stimulus in the very specific circumstance of making duration judgments but not identity judgments. This objection seems implausible because it amounts to the position that participants are blind to the digit unless they are asked if they are blind to it, at which point they will see the stimulus. Regardless, even if one were to adopt this position, it requires the additional assumption that after multiple trials, participants will not make the reasonable (and quite correct) inference that it is their saccades that trigger the stimulus sequence. If participants do make this causal link between the saccade and the onset of the stimulus, then to make post hoc changes to the estimations that participants have provided is highly questionable.

produced subjective-second estimates that were significantly shorter than an actual second.

Figure 2 illustrates the results from the individual subjects who participated in Experiment 2. We have shown the individual data to demonstrate that although the overall difference between conditions is significant, the pattern is far from reliable across subjects. Keeping that serious caveat in mind, the results suggest that the duration of the first digit is overestimated when its appearance is triggered by a voluntary action, be it an eye movement or a keypress response. The magnitude of the overestimation did not differ significantly between two responses. Together the data support a more general conceptualization of the chronostasis effect: Time tends to be overestimated for a sensory event that is perceived to result from any voluntary action. The trend towards overestimation in the no-action condition, together with the variability across individuals, however, suggests that caution is needed in interpreting this pattern.

Experiment 3: The Method of Adjustment

The results of Experiments 1 and 2 are consistent with the hypothesis that chronostasis is a general phenomenon reflecting the temporal binding of a perceptual event to the execution of a voluntary action. There was, however, a trend toward overestimation of the digit duration even in the condition in which no action was executed to initiate the sequence. Given the magnitude of this overestimation effect (85 ms), together with the variability of subject performance across conditions, we felt further investigation of the no-action condition was warranted. In Experiment 3, we repeated the keypress and no-action conditions, but we used a method of adjustment instead of a staircase procedure for measuring the subjective duration of digits in the sequence. Our pilot research had suggested that the method of adjustment would reduce within- and between-subject performance variability and, hence, produce a more precise measure of perception than the staircase procedure (see also Kelly & Savoie, 1973).

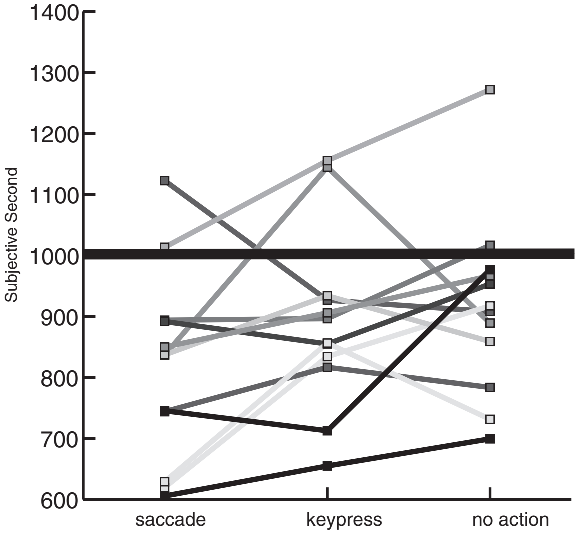

Figure 2. The duration of the first digit that appears to be equal to 1 s, termed a subjective second, is shown (in ms) for the saccade, keypress, and no-action conditions of Experiment 2. Each line represents the results from an individual subject.

Method

Sixteen naive subjects participated in the experiment. The method of adjustment was similar in practice to the staircase procedure in that, after each sequence, subjects had to judge the duration of the first stimulus relative to the others and the duration of the 1 on the subsequent trial depended on the response on the previous trial. Unlike the staircase experiments, in which subjects were not informed of the relationship between their response and the timing on the subsequent trial, in the present experiment subjects were specifically instructed at the beginning of each exploration to observe the sequence of events on each trial and then adjust the duration of the 1 to be shorter or longer on the subsequent trial. When they estimated the value of the 1 to be equal to the other digits, they would press the *Enter* key. Subjects were alerted that the program would not accept an estimate of equality until they had reversed their response at least twice, ensuring that the subjects explored both above and below the value they estimated to be equal. Each adjustment began with the duration of the first digit set to either 100 or 1,900 ms. Step sizes were initially 200 ms, and the step size was halved with each response reversal. Four adjustments were made for each condition. The methods were otherwise the same as those described in Experiment 1, except we examined only the keypress and no-action conditions.

Results and Discussion

Using the method of adjustment, we observed a significant difference between the keypress and no-action conditions of the experiment, $t(15) = 3.30$, $p < .01$. Both the keypress condition, 853 ms, $t(15) = 7.45$, $p < .001$, and the no-action condition, 935 ms, $t(15) = 2.70$, $p < .05$, produced subjective seconds that were significantly less than an actual second. From Figure 3, depicting the results from the individual subjects, it is clear that the method of adjustment produced a less variable estimate of a subjective second than the staircase procedure used previously.

An important result from Experiment 3 is the significant difference between the keypress and no-action conditions, which is consistent with the temporal-binding hypothesis in that it suggests voluntary action increases the perceived duration of the event that is triggered by it. In addition, the mean subjective-second value in the no-action condition (935 ms) indicates that the perceived duration of the first item in the sequence is overestimated regardless of whether an action is executed or not. This observation converges with previous research showing that the first item in a sequence (and to some extent the last item as well) appears to be longer in duration than the others, even in the absence of a voluntary action (Alexander et al., 2005; Rose and Summers, 1995). It is important to note that the existence of an overestimation effect in the absence of a voluntary action is not necessarily inconsistent with the temporal-binding hypothesis because the effect of action on perceived duration could be independent of other factors that might also distort perceived duration. That is, perceived duration could be influenced by the execution of an action to initiate a sequence, and it could also be influenced by the

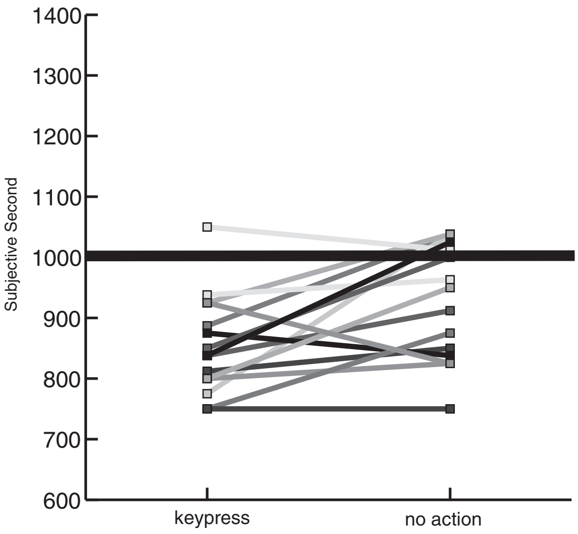

Figure 3. The duration of the first digit that appears to be equal to 1 s, termed a subjective second, is shown (in ms) for the keypress and no-action conditions of Experiment 3. Each line represents the results from an individual subject. There are several overlapping data points.

position in the sequence of the event being measured. The results of Experiments 2 and 3 support this interpretation, because the first digit was overestimated even when no action was executed, but it was overestimated to a significantly greater extent when an action triggered the sequence. Given that previous chronostasis experiments have focused exclusively on the first item in the sequence, it is important to explore the potential contribution of sequence effects to the phenomenon. In the next experiment, we examined the effect of voluntary action across all four items in the sequence.

Experiment 4: Perceived Duration of All Items in the Sequence

The temporal binding interpretation of the overestimation effect predicts that when an action initiates a sequence of items, the perceived time of the appearance of the first item in the sequence, but not the other items, should be bound to the action execution. This is why previous studies of the chronostasis effect have been concerned only with estimations of the first item in a sequence (e.g., Hodinott-Hill et al., 2002; Park et al., 2003; Yarrow et al., 2001, 2004). In Experiment 4, we compared the keypress condition to the no-action condition when all four digits in the sequence were judged an equal number of times. This experiment enabled us to measure the perceived duration of all four items in the sequence and shed light on the status of the first-digit duration relative to the others. We were also able to determine whether there is a systematic effect of the keypress for any of the other digits in the sequence.

One possible explanation for the overestimation of the first-digit duration in the absence of a voluntary action observed in Experiment 3 arises from the emphasis that the experimental context placed on the first digit in the sequence. Because only the first digit was adjusted, it follows that attention would be preferentially biased toward the first digit. It is well established that the duration of an item is perceived to be longer the more it is attended (the watched-pot illusion, e.g., Chaston & Kingstone, 2004). This could be a contributing factor to the chronostasis effect. Experiment 4 was designed to shed some light on this possibility because in it all the digits were adjusted equally often and, in this regard, all the digits were on equal footing.

Method

The methods were similar to Experiment 3, except all four digits were judged. A message appeared on the screen prior to each exploration to inform the subject of which digit to adjust (the 1, 2, 3, or 4) in the upcoming sequence (e.g., "now adjust the 3"). Sixteen participants adjusted each digit four times for both the keypress condition and the no-keypress condition (for a total of 32 adjustments for each participant). The order of adjustments was randomized.

Results and Discussion

The results are shown in Figure 4. A 4 × 2 repeated-measures ANOVA of position in the sequence and keypress revealed a main effect for which digit was adjusted, $F(3, 45) = 18.48$, $p < .001$, but no effect of keypress, $F(1, 15) = 2.15$, $p > .1$, and no interaction between these factors, $F(3, 45) = 1.30$. The only digit that appeared to be significantly less than 1 s was the fourth, one-group $t(15) = 5.45$, $p < .001$. None of the others differed significantly from 1 s, all ps $> .1$.

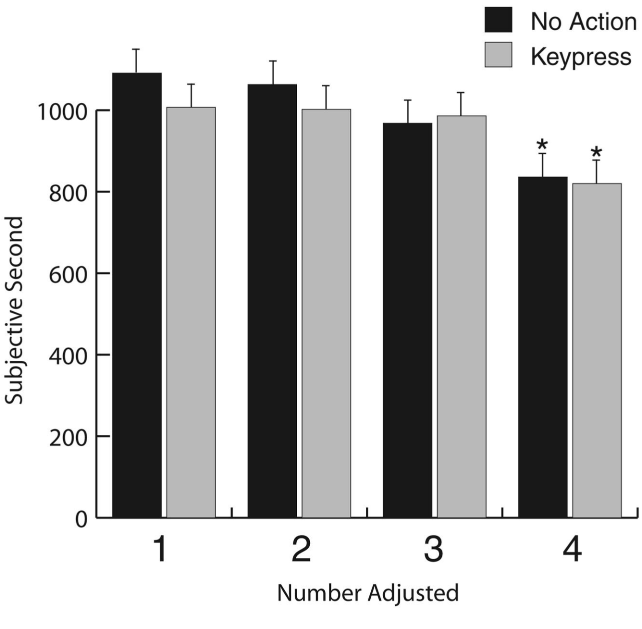

Figure 4. Subjective-second values are shown in ms for each of the four digits judged in Experiment 4. The sequence was initiated by a keypress or after a random interval (no action). Asterisks indicate conditions in which the subjective second was significantly less than an actual second. The error bars are calculated using the pooled error term of the factors and their interactions, according to the methods recommended by Masson and Loftus (2003) for representing significance levels in a within-subjects ANOVA.

It is clear from the results of Experiment 4 that time perception is distorted differently across the sequence of digits and that the increase in perceived duration that is taken as the signature of the chronostasis effect is actually larger for the fourth digit than for the first one. In fact, the duration overestimation of the first digit was eliminated even in conditions in which a voluntary action initiated the sequence of digits. If, as we proposed, a special status is allocated to the first digit when it is the only item adjusted in the sequence, it follows that duration overestimation might be abolished when all four digits are adjusted, as they were in this experiment. The lack of an effect of keypress on duration judgments in the present experiment is also problematic for the temporal-binding hypothesis. In the General Discussion of Experiments 1–5 section, we return to this issue more fully.

Experiment 5: Perceived Duration of the First and Last Digit

By equating the relevance of the digits in Experiment 4, the participants received more trials with the duration-perception task than they had in Experiments 2 and 3 or in previous chronostasis investigations. It is possible that this increased level of practice at judging item duration, rather than equating item relevance, resulted in more veridical judgments of the first item. In Experiment 5, we addressed this possibility by requiring that four groups of participants complete two blocks of trials. One group of participants judged the first digit in both blocks, and the other group judged the fourth digit in both blocks. A third and fourth group adjusted the first digit in one block and the fourth digit in the other block, with the order of blocks counterbalanced. This method allowed us to assess the effects of practice, order, and voluntary action on the perceived durations of the first and last digits.

Method

Forty-eight subjects were divided into four groups. Each group completed two blocks of eight explorations each. Group 1-1 adjusted digit 1 in both the first and second block, and Group 4-4 adjusted digit 4 in both the first and second block. Group 1-4 adjusted digit 1 in the first block and then digit 4 in the second block. Group 4-1 adjusted digit 4 in the first block and digit 1 in the second block. The method was otherwise the same as Experiment 4, with four adjustments for each digit in both the keypress condition and the no-keypress condition.

Results and Discussion

Six subjects were rejected for poor performance (according to the criteria described in Experiment 2), leaving 8 subjects each in Group 1-1 and Group 4-4, and 13 subjects each in Group 1-4 and Group 4-1. The results are illustrated in Figure 5. The manner in which the conditions are crossed in this experiment made many analyses possible. Four analyses were selected that would best assess the role of practice, order, and voluntary action on duration judgments of the first and last digit in the sequence.

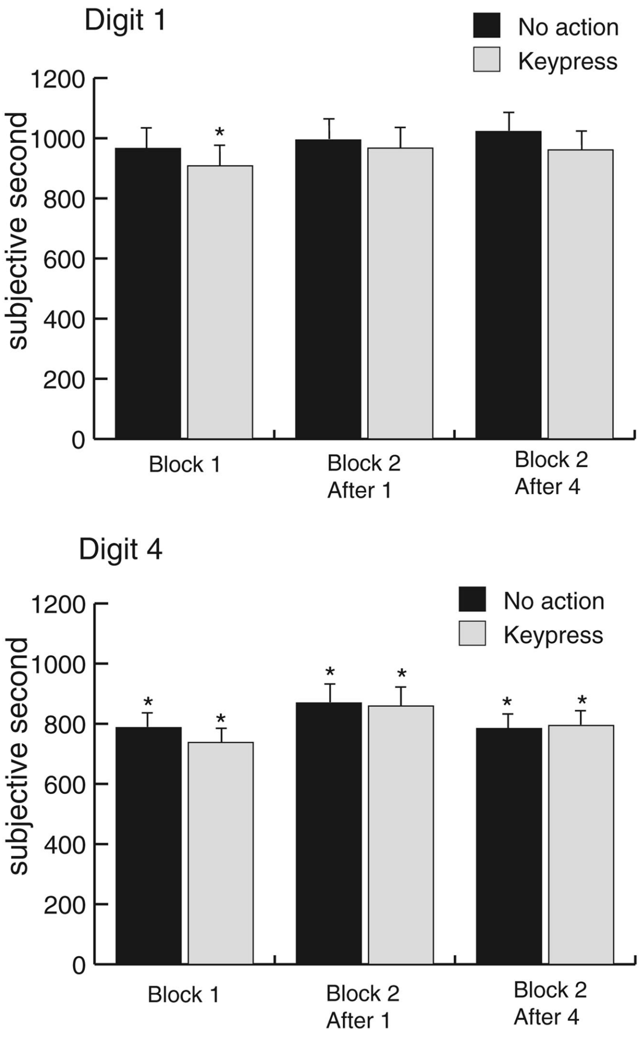

Figure 5. Subjective-second values in ms for the first and fourth digit in the sequence are shown for each of the four groups in Experiment 5. Asterisks again indicate subjective-second values that are significantly less than 1 s at the .05 level ($p < .05$). Because there were a total of 12 one-group comparisons made in this experiment, it is important to consider that some contrasts might be significant due to chance. After a Bonferroni correction, contrasts would have to have a p value of less than .0042 to be significant. All contrasts are significant at this more conservative level as well, with the exception of one condition: Subjective second values for digit 4, in the keypress condition, in block 2 after 4 (the rightmost column in the digit 4 graph) did not meet this significance level, $t(7) = 3.61$, $p = .009$. Error bars for within-subjects comparisons are calculated according to the methods recommended by Masson and Loftus (2003).

First, to assess the role of practice, the results from Group 1-1 and Group 4-4 were analyzed in an ANOVA with block (first or second) and keypress (keypress or no keypress) as within-subjects factors, and with digit (1 or 4) as a between-subjects factor. The effect of block gave us a measure of the practice effect, and the addition of the other factors allowed us to assess the effect of practice for keypress and digit conditions separately. There was a main effect of block, with a subjective second being significantly shorter in the first block than in the second, $F(1, 14) = 5.69$, $p < .05$, but no main effect of keypress, $F(1, 14) < 1$. There was a main effect of digit, with significantly shorter subjective seconds for the fourth digit than for the first, $F(1, 14) = 15.72$, $p < .001$. There were no significant interactions.

A second ANOVA examined the effect of the keypress for the first and the last digit. To accomplish this, data from the first block only were analyzed with digit (1 or 4) as a between-subjects factor and keypress as a within-subjects factor. The result revealed a main effect of digit, with significantly shorter subjective-second values for the fourth digit than for the first, $F(1, 40) = 40.99$, $p < .001$. There was also a main effect of keypress, with significantly shorter subjective-second estimates when a key was pressed to initiate the sequence than when it was not, $F(1, 40) = 11.44$, $p < .01$. The keypress effect did not interact with digit, $F(1, 40) < 1$, suggesting that the keypress effect was of a similar magnitude for the first and fourth digits in the sequence.

A third and fourth ANOVA, on the data from the second block only, was run to examine the effect of experience judging other digits in the sequence on time judgments in the second block only. In the first ANOVA, the second block of both the 1-1 group and the 4-1 group were analyzed, with group as a between-subjects factor and keypress as a within-subjects factor. Likewise, in the second ANOVA, the second block of the 4-4 group and the 1-4 group were compared, with group as a between-subjects factor and keypress as a within-subjects factor. For both ANOVAs, no main effects or interactions were significant.

Finally, the subjective-second values for each condition were also compared to an actual second. The duration of the digit 4 is overestimated in all conditions in which it was tested. The duration of the digit 1, in contrast, is only consistently overestimated in the keypress condition, and even then only when it is adjusted in the first block. It is important to note that this condition is essentially the same as those in which the first digit was tested in Experiments 2 and 3, in which the first digit was also overestimated. In the second block, it is no longer perceived to be significantly different from 1 s, suggesting that with practice, estimates become more accurate. This occurred whether or not the practice at the task in the first block was with the same digit or with another digit in the sequence, suggesting that the elimination of the overestimation effect in Experiment 4 was due to general practice at the duration-judgment task, rather than experience with judging other digits in the sequence. The keypress effect was also only significant when the first block was analyzed separately. Surprisingly, this first-block keypress effect did not interact with the digit, suggesting an effect of the keypress on perceived duration of the fourth digit as well as the first (see Figure 5, Block 1, Digit 1 and Digit 4).

It is interesting that subjective-second values for the fourth digit were consistently smaller than for the first digit. The only other duration-estimation study known to test other items in the sequence is Rose and Summers (1995), who showed that the durations of the first and last items were overestimated relative to the others. In contrast with the present findings, they observed a more consistent effect on the first item in a sequence than the last. The reason for this discrepancy is unknown, but one possibly important difference is that Rose and Summers had intervals between events, whereas the current study did not. In the current method, based on other chronostasis studies (e.g., Park et al., 2003; Yarrow et al., 2001; Yarrow et al., 2003), the last item is unique in being the only item that offsets without being replaced. This could serve to make it appear longer in duration than earlier items in the sequence. Regardless, this finding very clearly presents a problem for using the subsequent digits in the sequence as the standard against which the first digit is compared.

In sum, the results of Experiment 5 are at odds with the hypothesis that the duration-overestimation effect reflects the temporal binding of an action (in this case, a keypress) with its perceptual consequence because (a) judgments of the first digit became veridical with practice and (b) the overall effect of the keypress was not significant and, in the first block, in which it was significant, it was no larger for the first digit than the fourth. In addition, these results, when combined with the findings of Experiment 4, suggest that, among the four digits, it is more the last item in the sequence, rather than the first, that has a special status in terms of perceived duration.

General Discussion of Experiments 1–5

As discussed in the introduction, previous research on the chronostasis effect has produced at least two hypotheses about the cause and function of the distortion of time judgments during eye movements and other voluntary actions. The initial hypothesis was that the chronostasis effect reflects a mechanism for preserving perceptual unity while the visual world is moving across the retina during a saccadic eye movement. The alternative hypothesis predicted that any kind of voluntary action, including eye movements, would increase the perceived duration of a consequent perceptual event. The present evidence suggests that neither hypothesis can fully account for the overestimation effect.

In Experiment 1, we demonstrated that discrimination of events at the location of the saccade goal is possible. The important implication of this finding is that the subtraction of saccade duration from the subjective-second value is unwarranted, leading to the conclusion that the scaling effect observed previously was a byproduct of the erroneous subtraction of eye movement durations from subjective-second values. At least three empirical articles have applied this subtraction to subject estimates in conditions where eye movements triggered the onset of the to-be-judged event (Yarrow et al., 2001, 2003, 2004). In light of the present results, which indicate that this subtraction is based on a flawed assumption, certain key conclusions of these papers are brought into question, perhaps most importantly the conclusion that the function of chronostasis is to preserve perceptual unity during a saccade. In Experiment 2, we showed that without this subtraction, the chronostasis effect for the first item in a sequence of events is similar for keypress and saccadic responses.

In Experiment 3, we used the method of adjustment and observed a consistently larger duration overestimation of the first item in the sequence when the trial sequence was initiated with a keypress relative to the no-action condition. But we also observed subjective second judgments for the first item that were significantly less than 1 s even in the no-action condition, suggesting that at least some aspect of the overestimation effect is independent from the execution of a voluntary action. In Experiment 4, participants adjusted all four digits in the sequence. The result was that the overestimation of the first digit disappeared, even when a voluntary action initiated the sequence, and an overestimation effect for the last digit was observed instead. In Experiment 5 we sought to dissociate the action-based effects from task practice by examining the perceived duration of the first and the last digit. Overestimation of the duration of the last digit occurred consistently. The duration of the first digit was overestimated in the first block, replicating Experiments 2 and 3, but it became veridical in the second block. Again, there was no overall effect of executing an action to initiate the sequence of items.

It is difficult to account for this pattern of results purely in terms of temporal binding of actions to their perceptual consequences for the following reasons: (a) The perceived duration of the first digit can appear extended even when no voluntary action is executed, suggesting that other factors besides action cause events to appear longer in duration than they actually are. In other words, voluntary action is not necessary for perceived duration to be overestimated. (b) The effect of the keypress was no longer observed consistently in Experiment 4 and in the second block in Experiment 5, in which subjects had more practice at the temporal judgment task and judged other items in the sequence as well as the first one. Hence, voluntary action is also not sufficient for the effect to be observed. (c) The fourth digit is generally perceived to be longer than the first digit and also shows a similar keypress effect among unpracticed subjects. This result not only calls into question temporal binding as the mechanism driving the keypress effect but also implies that the baseline against which the first item has been compared in previous investigations may itself be distorted temporally (i.e., the baseline measure of 1 s cannot be assumed to be represented veridically, a point that is addressed in more detail later in this article).

The pattern of results from the present study, combined with the data from previous investigations, suggests that chronostasis is neither a mechanism for preserving perceptual continuity during saccadic eye movements nor a byproduct of temporal binding of perceptual events to voluntary actions. Several other factors are at play in chronostasis experiments that could be responsible for the pattern of results we and other investigators have observed. First and foremost, the perceived duration of visual stimuli clearly depends on their position in a sequence of items. This observation is supported by other behavioral studies (e.g., Rose & Summers, 1995) and also by recent observations suggesting that the position of the item in a sequence can determine how it is seen at very early levels of processing (Sharma, Dragoi, Tenenbaum, Miller, & Sur, 2003). Memory is an additional factor that previous time perception studies have shown to be important. The longer an interval has been retained in memory, the shorter it is remembered to have been (see Wearden & Ferrara, 1993; Wearden, Parry, & Stamp, 2002). A memory-based explanation could account for the results of Experiments 4 and 5, because the last item is retained in memory for a short period of time and should thus appear longer than the first item. Indeed, in Figure 4 there appears to be a linear trend from the first digit to the fourth, with subjective duration becoming increasingly shorter across the sequence of four items. An explanation based on recency alone cannot account for the chronostasis effect, however, because the first item appears to be longer than the others, not shorter, in Experiments 2 and 3 and in previous chronostasis investigations.

The issue of sequence and memory effects touched on above highlights several difficulties with interpreting the chronostasis effect using the typical methodology, in which the first item is compared to a sequence of subsequent items. Relative to other studies of time perception in human subjects, the original chronostasis methodology (e.g., Yarrow et al., 2001) is unique in comparing a single sample event to multiple standard durations. The basic problem with this method is that it is not known which of the durations are being taken into account in comparison to the first item, an issue that is of extreme importance if an understanding of the chronostasis effect is to be achieved. In more typical time perception studies, a single event's duration is judged relative to a single, constant standard, and the order of the standard and the comparison are counterbalanced to control for order effects (e.g., see Allan, 1979). Our final experiment used this method, which better controls for the effects of sequence and memory, to reassess the conclusions that have been drawn about the chronostasis effect both in this study and in previous studies.

Experiment 6: Perceived Duration in a Two-Item Sequence

In our final experiment, we compared keypress and no-keypress conditions in a two-item sequence. As we discovered in the preceding experiments, neither the item being judged nor the item it is being compared against can be assumed to be experienced veridically. Thus, any attempt to obtain an absolute veridical measure of perceived duration may not be particularly meaningful. However, using a sequence of only two items allowed us instead to obtain a relative measure of the perceived duration of the first and last items in the sequence. This approach has the advantage that it eliminates ambiguity about which item in the sequence is being used as the comparison stimulus, as there will only be one. It also allows for counterbalancing of whether the first or the second item in the sequence is being adjusted.

Experiment 6 provided one final test of the keypress effect. If the first digit is perceptually extended in time when a keypress initiates the sequence, subjective-second durations should be shorter for the first digit in the keypress condition relative to the no-action condition, as we saw in Experiments 2, 3, and 5. For the second digit, however, if the keypress increases the perceived duration of the first digit, subjective-second durations for the second digit will have to increase to match this increase relative to the no-action condition. Thus, the effect of the keypress should be to decrease the subjective-second value for the first digit and to increase the subjective-second value for the second digit, relative to the no-action conditions.

Method

Nineteen subjects participated in Experiment 6. The sequence of events in a trial was similar to Experiment 4, except that there were only two digits in the sequence (1 and 2). Subjects adjusted either the first or the second item in the sequence, and the sequence began when they pressed the space bar or after a random interval of 2–3 s. Subjects completed four adjustments for each condition. The order of conditions was counterbalanced. A two-factor within-subjects ANOVA was used to assess the main effects of the keypress, the digit being judged, and their potential interaction.

Results and Discussion

Three subjects were excluded for exceeding the variability criteria described in the *Method* section for Experiment 2. Whether or not a keypress initiated the sequence had no significant effect on the perceived duration, $F(1, 15) < 1$. The effect of digit (1 or 2) was significant, with the first digit adjusted to be 1,125 ms, and the last digit adjusted to be 960 ms, in order to appear to be equal to the other digit, $F(1, 15) = 18.651$, $p < .001$. There was no interaction between digit judged and keypress effects, $F(1, 15) < 1$ (see Figure 6).

We showed in Experiments 4 and 5 that a robust perceptual lengthening occurs for the last digit, and the results of Experiment 6 reinforce this finding. By adjusting the first digit to 1,125 ms, the participants are indicating that the second digit appears to last longer than the first. Similarly, by adjusting the second digit to 960 ms, the participants are indicating that the first digit appears to be slightly shorter than the second. Of course, because the perceived duration of one digit can only be understood relative to the perceived duration of the other digit, the most accurate conclusion is how one digit appears relative to the other. On this point the data are unequivocal: The perceived duration of the last digit is significantly longer than the perceived duration of the first digit.

The lack of an effect of the keypress for both the first and last digit in Experiment 6 is another indication of the weakness of the voluntary action effect. There were two opportunities for the action effect to express itself; the first digit subjective-second values should have been smaller in keypress than in the no-action condition, and the second digit subjective-second values should have been larger in keypress than in the no-action condition. Neither effect was observed. These data, combined with the findings from Experiments 4 and 5, indicate that the action effect is not especially robust. This conclusion agrees with the results of Yarrow et al. (2003), who also failed to replicate an effect of manual responses on duration judgments of visual stimuli in their control conditions.

Conclusions

To summarize, the present study answers at least three critical questions.

First, are there two types of chronostasis or one? It is clear that saccade durations should not be subtracted from estimates of the first-digit duration because subjects are able to perceive events that occur at the counter location during a saccade (Experiment 1). When no correction is applied to subject estimates, the magnitude of the overestimation does not scale with the length of the saccade. When we compared the chronostasis effect following saccades to the overestimation effect following manual responses (Experiment 2), there was no difference between the chronostasis effect for the two responses.

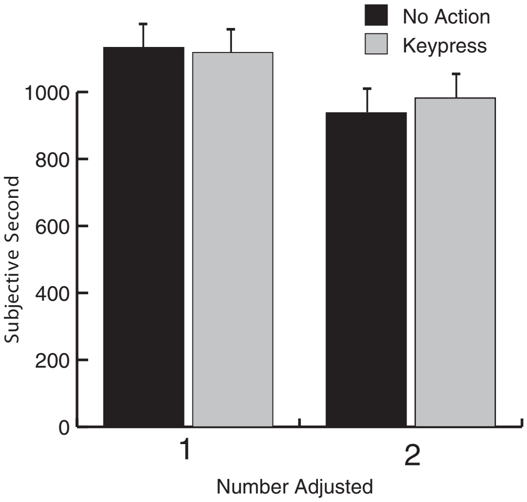

Figure 6. Subjective-second values for keypress and no-action conditions in Experiment 6, in which subjects adjusted the first and last digits in a two-item sequence. Error bars are calculated according to the methods recommended by Masson and Loftus (2003).

Second, does chronostasis reflect temporal binding to an action? Voluntary action is not necessary to produce an overestimation of the first digit (Experiment 3), nor is it sufficient (Experiments 4, 5, and 6).

And third, is overestimation specific to the first item in a sequence? The first-digit duration is not always overestimated relative to a 1-s baseline (Experiment 4, 5, and 6). When overestimation of the first digit does occur, it disappears with practice (Experiment 5). Moreover, it is the last item, and not the first item in the sequence, that was consistently overestimated (Experiments 4, 5, and 6).

Two conceptualizations of the chronostasis effect put forward in previous studies were that it reflects either a mechanism for preserving perceptual continuity during a saccadic eye movement and that it reflects the temporal binding of a perceptual event to the voluntary response that triggered it. Based on the above observations, it must be concluded that neither of these accounts are correct. Chronostasis is not unique to eye movements, and the overestimation of duration seems to occur among relatively unpracticed subjects and does not depend on the execution of a voluntary response (although we have not directly shown that the chronostasis effect for eye movement would be as fragile as the overestimation effect following keypress responses, without evidence that eye movements are unique, there is no specific reason to expect them to be less fragile).

What then does the overestimation effect reflect? The original chronostasis methodology introduces several complex factors to time perception, any of which could contribute to distortions in duration judgments. Postulating that these distortions are a direct effect of an eye movement or other action is inconsistent with the fact that the interval is not perceived accurately in the first place. A similar point is made by Freeman and Banks (1998), who showed that distortions of perceived velocity once thought to be due to systematic errors in correcting for eye movement velocity are actually due to systematic errors in motion perception more generally. In that case and the current situation, a failure to account for limitations in perception under normal circumstances has led to the spurious conclusions about the limitations in temporal perception during more complicated circumstances, such as eye movements and other voluntary actions.

Memory, in particular, is a plausible explanation for why the last digit duration was perceived as the longest item in the sequence, because the perceived duration of an item tends to decline the longer it is retained in memory (Wearden & Ferrara, 1993; Wearden et al., 2002). Thus, the last item may be seen as the longest in duration because it has been retained in memory for the shortest period of time and because it is compared against items that have been retained for longer periods of time. Directed attention is another potentially important factor to take into account, as previous studies have shown that focusing attention on a brief event can make it appear prolonged (e.g., Coull, Vidal, Nazarian, & Macar, 2004; Enns, Brehaut, & Shore, 1999; Mattes & Ulrich, 1998). This mechanism could be at work in Experiments 2 and 3, in which the first item was the only item that was judged and the only item that varied in duration. It is reasonable to think that, in this situation, attention would be allocated more to the first item than to the subsequent items, thus prolonging the perceived duration of the first item. In support of this hypothesis, practice was shown to eliminate the overestimation of the first digit. Practice would facilitate withdrawal of attention from the time-estimation task. An attention-based explanation of chronostasis can also account for the subjective experience of the watched-clock illusion, which is frequently referred to as a real-world example of the chronostasis effect. The illusion is experienced when one first looks at a ticking analog clock face and it appears to take the second hand more than a second to move to the next position. Similar illusions of time are experienced in the auditory domain (for instance, when listening to the ring tone on a telephone receiver, Hodinott-Hill et al., 2002). These experiences could be attributed to an initial increase in attention to the duration of a new event that causes these events to appear to last longer than expected.

Future Directions

Time estimation was clearly a difficult task to perform with any precision in the present study and in those like it (e.g., Hodinott-Hill et al., 2002; Park et al., 2003; Yarrow et al., 2001). The large variability both between and within subjects and the number of subjects rejected for highly variable performance both suggest that few subjects found the time-estimation task easy. The apparent difficulty of time estimation belies the fact that, in our daily lives, we estimate time with great precision in the course of most activities we undertake. Consider, for example, driving a car or playing music, sports, or computer games. The primary difference between more naturalistic tasks, such as these, and the timing tasks used in investigations of time estimation is that the explicit report and comparison of remembered duration values is not a normal component of precisely timed activities. The millisecond precision with which humans can perceive time in more naturalistic settings suggests that explicit reports of time perception may not be very reflective of one's true capabilities. Several cognitive factors that are at play in laboratory-based time-estimation tasks, such as memory, attention, sequence effects, and practice, could contribute to the variability of responses when explicit report of remembered durations is used to measure the perception of time. Some research has begun to bridge this gap in our understanding by examining predictive time estimation, using more natural tasks, such as estimating the impact time of a thrown ball, with or without visual trajectory information (e.g., Grealy, Craig, Bourdin, & Coleman, 2004; Huber and Krist, 2004). Future research should explore how perceived durations in explicit, off-line judgment tasks differ from those perceived in more implicit, everyday, online time-perception activities (see Kingstone, Smilek, Ristic, Friesen, & Eastwood, 2003; see also Kingstone, Smilek, & Eastwood (in press), for a fuller discussion of this general issue). In the meantime, a more complete understanding of how time perception is affected by motor processes may result from experiments in which subjects use online, implicit time information to guide performance.

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