# attention and time

## and time

### Edited by
### Anna C. Nobre
### Jennifer T. Coull

Our ability to attend selectively to our surroundings - taking notice of the things that matter, and ignoring those that don't - is crucial if we are to negotiate the world around us in an efficient manner. Several aspects of the temporal dimension turn out to be critical in determining how we can put together and select the events that are important to us as they themselves unfold over time. Surprisingly, this fascinating and fundamental interplay between 'attention' and 'time' has been relatively neglected in the psychology and neuroscience literatures until very recently.

*Attention and Time* is the first book to address this fundamental topic, bringing together several intriguing and hitherto fragmented findings into a compelling and cohesive field of enquiry. The book contains thirty-one critical-review chapters from internationally recognized experts in the field, carefully organized into three stand-alone, yet extensively cross-referenced, themed sections. Each section focuses on distinct ways in which attention and time influence one another. These sections, each encompassing a range of methodologies from classical cognitive psychology to single-cell neurophysiology, provide functionally unifying frameworks to help guide the reader through the many various experimental and theoretical approaches adopted. Section One considers variations of attention across time, and explores how attentional allocation is limited by very short or very long intervals of time. Section Two describes several types of temporal illusion, illustrating how attention can modulate the perception of the passage of time itself. "A watched pot never boils" and, conversely, "time flies when you're having fun" nicely capture the experimental observation that the degree of attention allocated to stimulus timing contributes to its subjective duration. Finally, Section Three examines how attention can be directed in time, to predictable or expected moments in time, so as to optimize behaviour.

Bringing conceptually discrete, yet functionally related, fields of temporal attention research together within a single volume, this book provides a comprehensive overview that will be of value to the interested novice in cognitive neuroscience, whilst also inspiring experts in the field to make, perhaps previously overlooked, links with their own field of research.

## Chapter 10

# Attention underlies subjective temporal expansion

## Peter Ulric Tse

Perhaps you have noticed that events sometimes seem to slow down transiently. I first noticed this as a schoolboy, eager for class to be over. I noticed that when I first looked at the analogue clock, whose second hand jumped each second, that it seemed that the second hand had stopped, at least initially (see Yarrow, Chapter 12, this volume). After an inordinately long time it seemed to move again, and return to its usual pace. Now I notice this when I come home at night, and cannot initially tell whether the red light on my answering machine is blinking or not, because the first blink seems so inordinately long (compare Rose and Summers, 1995; Kanai and Watanabe, 2006). This temporal expansion has also happened to me in circumstances where my attention has suddenly been brought into focus, as when I swerve to miss a deer that has jumped onto the road, or as I watch myself helplessly skid into the back of another car. Why does this illusion of conscious experience occur? This chapter explores this question by summarizing key findings of Tse and colleagues (Tse, Sheinberg, and Logothetis 2004), and then discussing them in terms of more recent findings from the time-perception literature.

The perception of duration is rooted in the perceptual processing of events. In cases of prospective duration judgements (i.e. when observers know that the experiment is about judging durations), when no concurrent processing of stimuli is required, the ratio of judged duration to real duration generally *increases* as a function of both the number of stimuli that occur over an interval (e.g. Frankenhauser, 1959; Fraise, 1963; Ornstein, 1969; Thomas and Brown, 1974) and the complexity of those stimuli (e.g. Schiffman and Bobko, 1974; Avant, Lyman, and Lee, 1975; Thomas and Weaver, 1975). However, when observers must process non-durational information about stimuli during prospective tasks, or when they must perform a concurrent task, the ratio of judged to real time generally *decreases* as a function of the amount of information processed (e.g. Katz, 1906; Hülser, 1924; Quasebarth, 1924; Underwood and Swain, 1973; Hicks and Brundige, 1974; Hicks, Miller, and Kinsbourne, 1976; Thomas and Cantor, 1978; Zakay and Tsal, 1989; Grondin and Macar, 1992; Zakay, 1993; Macar, Grondin, and Casini, 1994; Predebon, 1996). Duration estimations therefore follow opposite trends in prospective experiments that involve concurrent processing and those that do not. In the absence of concurrent processing, subjective time expands whereas in its presence, it typically contracts. Here I explore the temporal dynamics of subjective temporal expansion (henceforth referred to as just 'temporal expansion') and describe the role of attention in this illusion.

An extensive literature provides evidence for the hypothesis that attention plays a role in the perception of duration (e.g. James, 1890; Katz, 1906; Mattes and Ulrich, 1998). Building on earlier models (Creelman, 1962; Treisman, 1963), Thomas (Thomas and Brown, 1974; Thomas and Cantor 1978; Thomas and Weaver, 1975) and Hicks (Hicks, Miller, and Kinsbourne, 1976; Hicks et al., 1977) proposed an attentional allocation/distraction model according to which attention can

increase (or decrease) the perceived duration of a unit of objective time. If attention is distracted by non-temporal information processing, less capacity is available for processing temporal information (Kahneman, 1973), and duration judgements will tend to decrease or become less reliable (Brown, 1985; Brown, Chapter 8, this volume). If attention is not distracted from temporal information processing, then more capacity is available for processing temporal information, and duration judgements will tend to increase. In agreement with Fraisse (1963), these authors argue that the prospective judgement of time requires attention to the passage of time. Concurrent processing entails a relative underestimation of clock time because the observer must attend to the distracting task rather than to the passage of time. When not paying attention to cues for the passage of time, the observer misses more such cues, causing underestimations of clock time. Fraisse (1984) found evidence supporting this model (Thomas and Cantor, 1978). In particular, the easier a concurrent task, the more observers tend to overestimate an interval, presumably because when a distracting task is easy, observers are able to attend more to duration.

According to these models there is a 'counter' that keeps track of the number of units of temporal information processed for a given perceived event (Treisman, 1963; Thomas and Weaver, 1975).[1] These models argue that the number of units of temporal information that are counted decreases when attention is distracted from processing the duration of an interval. According to these models, attention increases duration judgements when duration per se is attended because fewer temporal cues are missed. However, the data of Tse and colleagues (2004) suggest that it is also possible that the number of units of temporal information processed is boosted above baseline when an observer orients to an improbable event. If attending to a stimulus boosts information processing of that stimulus, then the counter would count more units, and subjective time would expand (but see Eagleman, Chapter 11, this volume). The 'missed temporal cues' and 'attentional boost' interpretations are not mutually exclusive. Both could contribute to distortions in perceived duration and both are compatible with the notion of a counter or some other as yet unknown neural mechanism that measures the amount of information processed per unit objective time in order to calculate the duration of perceived events. That is, on both accounts, that of Thomas and Weaver (1975) or Tse et al. (2004), if the amount of information processed per unit objective (i.e. clock) time, particularly information about duration per se, increases or decreases, the perceived duration of an event changes accordingly.

The majority of research in the time literature therefore supports, dare I say, a 'standard attentional model' of time perception according to which paying more (less) attention to the duration of an event increases (decreases) its perceived duration (Brown, Chapter 8, this volume). Questions remain, however. Is the expansion in perceived duration really an attentional effect, or is it simply a consequence of the amount of information processed? If attention increases the amount of information processing brought to bear on a stimulus, it might be difficult to separate these two possibilities. However, a strictly attentional account would make at least four predictions that a (non-attentional) speeded information-processing account would not. First, at least 80–150ms are required before attention can be allocated to a new stimulus (e.g. Nakayama and Mackeben, 1989; Hikosaka, Miyauchi, and Shimojo, 1993). If it can be shown that there is an expansion of perceived duration for objective durations above ~120ms, but a contraction for durations below ~80ms (because attention is not yet fully allocated to the stimulus), then this would support an attentional account. Second, attention is commonly believed to have two components, one transient (or exogenous) and one sustained (or endogenous) (e.g. Nakayama

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[1] In the literature on duration perception the terms 'unit,' 'cue,' and 'pulse' are used equivalently in the context of clock/counter models.

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and Mackeben, 1989). These two attentional components have different temporal dynamics, and this difference should manifest itself in duration-estimation data. Third, attention is a central process, and should therefore exert its effects in the visual and auditory modalities in a similar fashion. Lastly, there is extensive evidence that attention cannot be applied to the pattern of low-level retinal activation itself. Rather, attention can only be allocated over information that has been processed by grouping, shape formation, and other processes that operate pre-attentively (e.g. He and Nakayama, 1992; Baylis and Driver, 1995; Rensink and Enns, 1995). Temporal expansion should therefore not be a function of image novelty per se but instead should be a function of the novelty of pre-attentively processed information.

Tse and colleagues (2004) carried out a series of experiments to test these predictions. Their experiments explored the role of attentional orienting in the subjective expansion of time by testing both visual and auditory stimuli within an oddball paradigm. In an oddball paradigm the observer responds to a low-probability stimulus that occurs within a train of high-probability stimuli. An oddball paradigm was used because: (1) a 'transient' or 'exogenous' component of attention is allocated automatically to the abrupt onset of a new stimulus (e.g. Nakayama and Mackeben, 1989; Remington, Johnston, and Yantis, 1992), and (2) a large literature shows that detection of an oddball typically leads to marked changes in event-related potentials that are believed by many researchers to be highly sensitive to attentional mechanisms (e.g. the P3 is highly dependent on attention; Polich, 1986; Garcia-Larrea, Lukaszewicz, and Mauguiere, 1992; Potts et al., 1996). Since observers tend to orient and thus attend to an oddball quite automatically, an oddball paradigm offers certain advantages over experimental paradigms that manipulate 'willed,' 'sustained,' or 'endogenous' attention to stimuli. In particular, since the present research focuses on the temporal dynamics of temporal expansion, an oddball paradigm afforded us good control over the timing of observers' allocation of attention.

The goal was to describe the objective temporal dynamics of distortions in subjective time as events are experienced in the present. Some researchers have called the amount of experience sustainable within a short-term memory store the 'psychological present,' (Fraisse, 1963; Michon, 1978) and argue that it has an upper limit of 5 seconds and an average value of 2–3 seconds (Fraisse 1984). We therefore limited our research to an examination of distortions in the 75–4000ms range; longer durations most likely involve memory processes beyond those of short-term memory, and temporal expansion is an illusion of how long something seems to last now, not of how long something seems to have lasted minutes or years after the event.

## Subjective temporal expansion of an oddball stimulus

Experiment 1 tested how the subjective duration of oddball stimuli compared to that of standard stimuli. The oddball stimulus was a solid black disk that grew smoothly in size, whereas the standard was a solid black disk that did not move, and was the same size as the initial size of the oddball. It was determined how long a visually expanding oddball would have to last in objective duration in order to have the same subjective duration as stationary standards. An oddball event of variable clock duration was placed in a temporal sequence of standards, each of which lasted 1050ms. The observers' task was to say whether the moving oddball stimulus lasted longer or shorter than the standards. In order to obtain a psychometric function, the oddball was presented at nine objective durations (450, 525, 600, 675, 750, 825, 900, 975, 1050ms) around a central duration in randomized order. So that observers could not know when the oddball would appear, a variable number of standards appeared between two oddballs. Observers were told that all standards were of constant duration, which was the case. Standards were available both before and after oddball presentation and observers were encouraged to use both these standards in making their

judgement of duration relative to the standard; they could respond until the start of the second standard following an oddball. All stimuli were separated by an interstimulus interval that varied randomly around 1050ms in the range 950–1150ms. The irregular temporal spacing of stimuli ensured that observers responded to the duration of stimuli per se, rather than the rhythm or beat that would be created if the interstimulus interval were held constant. The point at which the observer responded 'longer' on half the trials was taken to be the point of subjective equality obtained from Weibull fitted curves. The average point of subjective equality was 675ms Thus an oddball (an expanding solid disc) lasting 675ms was judged to feel, on average, as long in duration as a standard lasting 1050ms. This was the strongest example of subjective temporal expansion found using the oddball paradigm.

## Temporal dynamics of temporal expansion

In Experiment 2, the hypothesis was tested that observers overestimate durations only after a temporal delay which corresponds to the number of milliseconds necessary for attention to be allocated to a new stimulus after onset of that stimulus. Again, a dynamically growing oddball of variable clock duration was placed within a train of standard events of constant clock duration. The observers' task was to say whether the oddballs lasted longer or shorter than the standard events. By repeating the procedure for standards of different durations, it was possible to determine the points of subjective equality between oddballs and standards around different durations. For each of the standard durations tested (75, 135, 225, 375, 525, 1050, 2100ms), the oddball was tested at nine objective durations around a central duration chosen to span a range that would permit the plotting of a psychometric function.

The ratio of 'perceived to real' durations was obtained by dividing the veridical duration of the standard by the subjective duration for the oddball as shown in the following formula: temporal expansion factor = (standard duration)/(point of subjective equality of oddball). The averaged data (arithmetic mean) for the visual expanding oddball among non-expanding standards is shown in Figure 10.1A. Note that there is no overestimation of duration for the 75-ms case. Indeed, there is *underestimation* for the oddball at this low standard duration. However, already by 135ms, there is considerable overestimation of the oddball's duration.

According to the standard attentional model, subjective durations are a function of the amount of temporal information processed over a perceived stimulus per unit objective duration. If an increase of information processing occurs, subjective durations will seem longer than they might otherwise. These results support the standard attentional model. Interestingly, time does not appear to expand subjectively until 75–120ms after stimulus onset. This result is consistent with the view that duration overestimation is a function of the allocation of attention, because attention presumably takes some time to allocate to the oddball target after it is detected.

But why would there be a reverse effect, or subjective temporal contraction, for the 75-ms case (compare Nakajima, ten Hoopen, and van der Wilk, 1991; Nakajima et al., 1992)? If attention boosts the amount of information processed, then the allocation of attention will boost perceived durations. However, it takes time to allocate attention. One possibility is that there is a momentary decrease in the amount of temporal information processed, perhaps because attention cannot be allocated to a stimulus while it is being shifted to that stimulus. This decrease relative to the baseline rate of information processing would be experienced as a subjective contraction of time. Another possibility is that some information about a stimulus is lost before attention can be fully allocated to a stimulus. Information loss would lead to a relative shortening of perceived duration. Another possibility is that when the oddball target is detected at this brief duration, attention may only be allocated after the target stimulus has disappeared. After the blank interstimulus
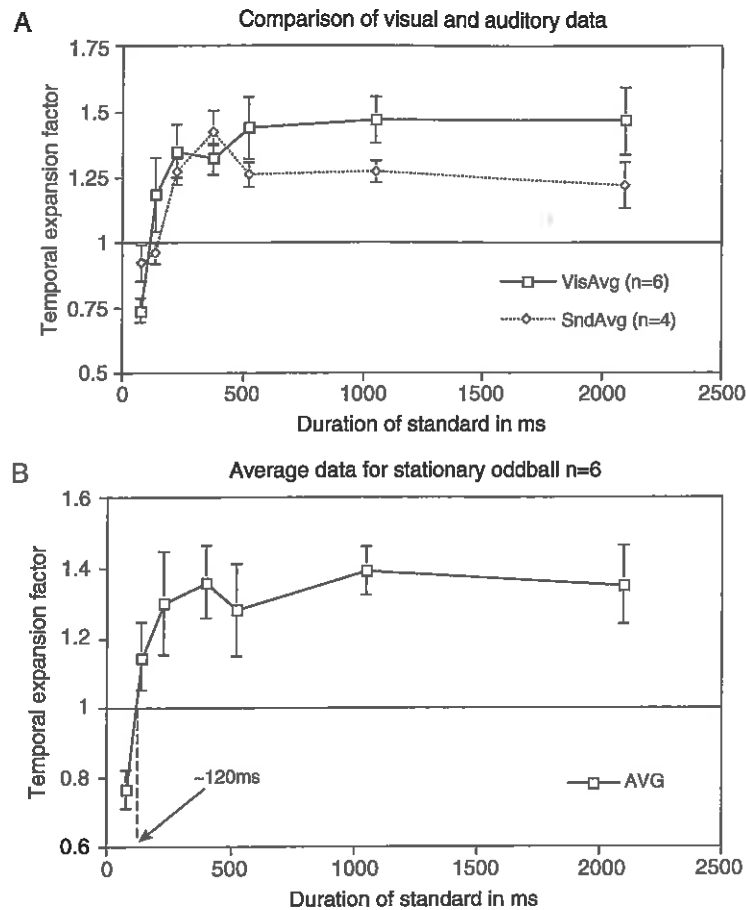
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**Fig. 10.1** A) A comparison of the temporal dynamics of subjective temporal expansion for both the visual (VisAvg) and auditory (SndAvg) domains. B) Average data for a non-expanding (stationary) oddball among expanding standards using the method of constant stimuli, with standard errors of the mean indicated by error bars.

interval, a standard stimulus appears on the screen. Because attention is now allocated to *this* stimulus, it is this standard disc that undergoes temporal expansion. In relative terms, this standard will seem to last longer than the target that preceded it, and observers may therefore respond 'shorter' for the target more often than not. Another possible contributing factor may be that the blank interstimulus interval after oddball disappearance gets expanded. This may make the oddball, in retrospect, seem shorter. The temporal dynamics of attentional allocation may therefore contribute to subjective temporal contraction in more than one way.

An interesting observation about the curve shown in Figure 10.1A is that it has a dip centred at 375ms, and a local peak at 225ms. This peak and dip pattern is more consistent in the individual data (not shown). Of six observers, only one did not demonstrate a peak followed by a dip then followed by a rise in the temporal expansion factor. Indeed, because the dip occurs at different times for different observers, the size of the peak and dip is somewhat attenuated in the averaged data shown in Figure 10.1A. Assuming attention is fully allocated to a stimulus only

~75–120ms or more after the onset of that stimulus, this local peak would occur at ~100ms after attentional allocation. Thus this local peak happens in the neighbourhood of 175–220ms after cue onset.

If this peak-dip-rise pattern reflects real underlying processes, it is consistent with the existence of transient and sustained components of attention (Nakayama and Mackeben, 1989; see also Olivers, Chapter 4, this volume). The transient component has a sudden onset, followed by a rapid decline, and the sustained component rises more slowly, but does not fade as rapidly. According to Nakayama and Mackeben (1989), the transient component peaks in the neighbourhood of 100ms after cue onset and begins to rapidly decline approximately 200ms after cue onset. The transient-peak in their data therefore tends to occur more rapidly than the peak in our data[2]. In contrast, the sustained component of attention does not peak and decline, but instead increases logarithmically with time. If attentional effects are due to the superposition or summation of these two types of attention, one transient, fast, and involuntary, and the other slow, sustained, and voluntary, then there may be a point where the effects of the former have begun declining before the effects of the latter have become strong. Such a point would look very much like the dip that we see in our data.

In summary, the data shown in Figure 10.1A are consistent with a model of time estimation based on attention according to which: 1) the amount of temporal expansion increases with the amount of information about duration processed and 2) attention enhances such information processing. Our data are consistent with the notion that attention takes in the order of 75–120ms to engage once an oddball stimulus has been detected. The data from individual observers suggest that a transient component of attention peaks within approximately 100ms following initial engagement. As the transient component weakens, a sustained component of attention becomes dominant. It may be that the transient component induces a burst of temporal information processing that is greater than the rate of information processing that occurs during the sustained component phase. Therefore the temporal expansion factor hits a peak with the peak of the transient component, but stays above unity because of enhanced information processing due to the sustained component of attention.

## Temporal expansion for a stationary oddball

In the experiments described earlier, the occurrence of the oddball was confounded with the occurrence of expanding motion. Another potentially confounding factor was the rate or velocity of radial expansion, which depended on the duration of the oddball, because the ball had to grow from its initial to its final size within the time afforded by the allotted duration. Brown (1995; Chapter 8, this volume) has shown that a moving stimulus tends to undergo more temporal expansion than a stationary stimulus of identical objective duration, and that faster speeds tend to lengthen perceived time more than slower speeds. Similarly, Fraisse (1963) argued that judged duration is a function of the number of perceived changes. Since a radially expanding stimulus has more perceived changes per unit objective duration than a stationary stimulus, the temporal expansion observed might be a consequence of change perception, rather than attentional orientation to an oddball. To address these potential confounds, the oddball in Experiment 3 was a stationary ball placed among a sequence of expanding standards.

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[2] The reason for this is unclear, but may be due to the differing nature of the two experimental paradigms. Their task is an attentional response to cue onset, whereas ours involves making a duration judgement based on novelty detection under conditions of sustained endogenous attention to the stimuli, necessitating a comparison between the oddball and the standards, which may cost additional time.

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It might be that the pattern of results shown in Figure 10.1A is not a consequence of the target being an oddball so much as it is a consequence of the target being a more salient stimulus. Thus, in this experiment, the roles of target and standard in Experiment 2 were reversed so that the oddball was a stationary disc among expanding standards.

The results are shown in Figure 10.1B. Although the magnitude of temporal expansion was less than in the two previous experiments (~1.2 here versus ~1.6 for Experiment 1 and ~1.45 for Experiment 2 at 1050ms; compare Figure 10.2B), the overall pattern of results is very similar. Again, temporal expansion occurs beyond ~75–120ms and there is a peak-dip-rise pattern, although the peak occurs later in this case than in Experiment 2. This trend is also discernible in the individual data.

Although we cannot say with certainty what delays the peak in temporal expansion in Figure 10.1B relative to Figure 10.1A, it is not solely the motion of the oddball that induces temporal expansion. Rather, it is the fact that the target stimulus is an oddball to which the observer must respond that underlies temporal expansion. It could be that attentional orienting to a moving stimulus is faster than it is to a non-moving stimulus. An extensive recent literature has shown that exogenous attention is allocated automatically and rapidly to a sudden onset or motion (Jonides and Yantis, 1988; Yantis and Jonides, 1990; Remington, Johnston, and Yantis, 1992; Yantis and Egeth, 1999; Tse, Irwin et al., 2000; Sheinberg, and Logothetis, 2001). Moreover, if attention is already at an elevated level because the standards are moving, the boost in attention afforded by the stationary oddball's novelty may take longer to rise to its peak level.

It is likely that oddball motion contributed to the magnitude of temporal expansion in the case of the expanding oddball, because the oddball was salient not only due to its relative novelty, but also due to its motion. In the converse experiment, where standards moved, and the oddball did not, however, it is likely that the inherent salience of the moving standards diminished the strength of temporal expansion. This weakening of temporal expansion might have had at least two non-exclusive causes. First, more attention may have been allocated to the standards, raising the 'baseline' level of processing from which orienting to the oddball occurred. Second, the oddball may have drawn less attention to itself, because of its relatively lower salience.

## Temporal expansion for colour, form, and size oddballs

In other experiments, we determined whether temporal expansion occurs for various other types of oddball stimuli, presented within a series of 1050-ms standards. We tested a red stationary disc as an oddball among black stationary discs of the same size; a circle among squares; a square among circles; and a large disc among small discs. The results for these oddballs are compared to those for the expanding and stationary oddballs from the previous experiments in Figure 10.2.

The strongest effect occurs for an expanding oddball among stationary standards (Experiment 1), where inter-observer variability was also the lowest. The weakest effect occurs for a stationary oddball among expanding standards (Experiment 2). The other four cases are intermediate, but generally support the notion that whenever an observer must detect and respond to an oddball stimulus, its subjective duration will expand. The same data have been replotted in Figure 10.2B in terms of the temporal expansion factors found in the various conditions.

## Temporal expansion for an auditory oddball

If the curve shown in Figure 10.1A is due to the effects of a central process such as attention, rather than a specifically visual process, then repeating Experiment 2 using a sound analogue of the standards and expanding oddball should result in a similar curve. Alternatively, if the process is specifically visual, then we might expect a different pattern of results. This experiment used two
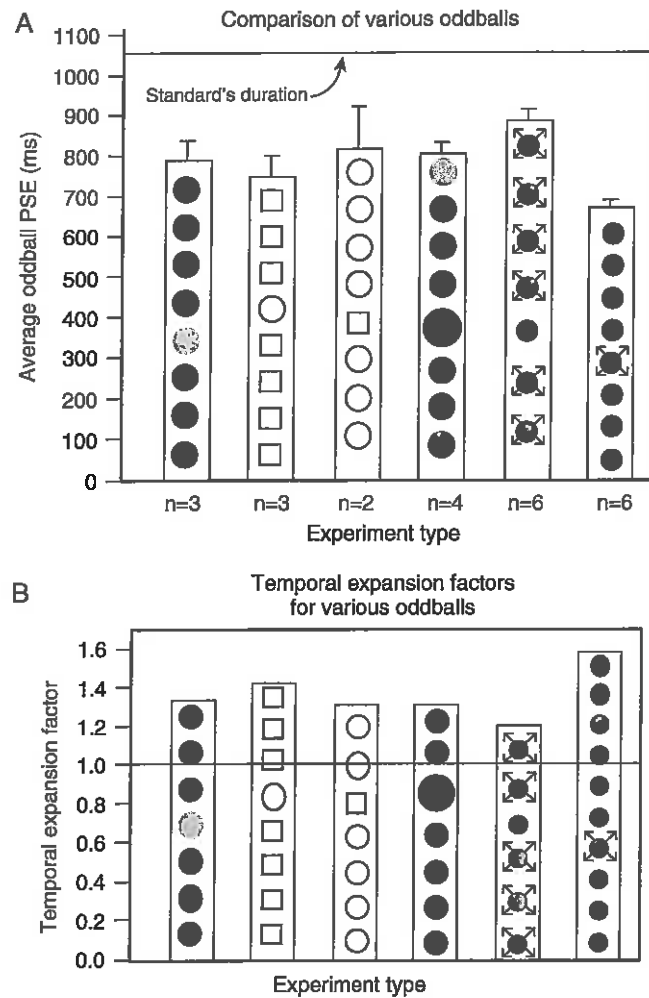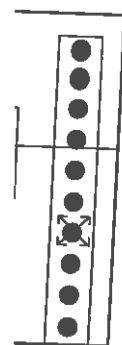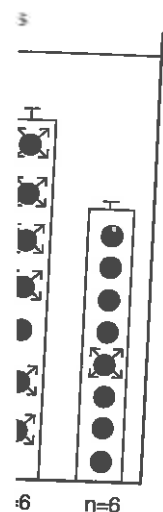
**Fig. 10.2** A) Points of subjective equality (PSE) for six types of oddball/standard combination. The pattern within the bars of this bar graph is meant to indicate the type of standard and oddball stimuli used. For the sake of comparison, the final two bars illustrate the results from Experiments 1, 2, and 3. The rightmost bar indicates an expanding oddball among stationary standards. The second bar from the right indicates the stationary oddball among the expanding standards of Experiment 2. The new data are shown in the four bars starting at the left. The leftmost bar was a red stationary oddball among black stationary standards. The next bar to the right shows data for a disc oddball among square standards, and the next bar shows the inverse case. The fourth bar shows data for a large oddball (radius 100 pixels) among smaller standards (radius 30 pixels). The number of observers used in each case is indicated at the base of each bar. Error bars indicate standard errors of the mean. B) The same data now in terms of temporal expansion factors.

types of tones presented with stereo headphones; the standard tone was a pure sinusoidal tone set at middle C and the oddball tone was a smoothly rising tone that started at 20 half-notes below middle C and rose to 30 half-notes above middle C. Special care was taken to control the timing of this oddball. In all other respects, the experiment was identical to Experiment 2, and used the method of constant-duration standards and random inter-trial intervals.

Of particular interest is the relationship of the averaged data for this auditory experiment and the curve for its visual analogue. To make the relationship of these two curves apparent, they have been overlaid in Figure 10.1A. Even though there is more temporal expansion for the visual case at longer durations, the basic pattern of results is similar for the visual and auditory conditions. Indeed, the auditory data are virtually identical to the visual data for a stationary oddball among expanding standards (Figure 10.1B). We therefore conclude that temporal expansion is due to a central process, such as attention, that can express itself similarly in both the visual and auditory channels. We would predict that the temporal dynamics visible in Figure 10.1A would be present even if the stimuli were presented haptically, or in some modality other than vision or audition. However, we predict that subjective expansion of time would be undermined if attention were diverted, or even damaged as in neglect or Balint's patients.

Our data partly corroborate those of Nakajima and colleagues (Nakajima et al., 1991; Nakajima, ten Hoopen, and van der Wilk, 1992; see Allan and Gibbon, 1994), who reported that empty durations seem relatively shorter than a preceding 50-ms standard when the duration of the test stimulus is less than 120–160ms. However, they do not find temporal expansion beyond 160ms as we do, but report that 'time-shrinking' merely disappears. This could be because they were studying empty intervals, whereas we are studying intervals filled with events. Subjective temporal expansion may not be as strong an effect for empty intervals because there is nothing to attend to in empty intervals.

Note that both the visual and auditory curves in Figure 10.1A suggest that temporal expansion begins to occur in the neighbourhood of 120–150ms. This is consistent with the hypothesis that a brief span of time is required before attention can be allocated to a stimulus following stimulus onset. In addition, note that the auditory curve also has a peak that is suggestive of a transient component. However, its peak occurs 150ms after the local peak at 225ms for the visual curve. This trend is not an artefact of averaging data across observers. In Figure 10.1A, the peak occurs (for five of the six observers who do have a peak) between 135ms and 375ms, with four of the six observers demonstrating a peak at or before 225ms. In contrast, all four observers in the auditory condition demonstrate a peak at 375ms. The reason for this is unclear, but may be due to differences in the temporal dynamics of the transient and sustained components of attention in different sensory modalities. On the other hand, the peak and dip in the visual data shown in Figure 10.1B, where the oddball is a stationary disc among expanding standards, occurs at the same durations (375ms and 500ms respectively) as for the auditory data. Thus, slight differences in the locations of the peak and dip may be less important than the fact that there is a peak and dip in both the auditory and visual sense modalities. We take the existence of a peak and dip followed (at least in the visual cases shown in Figures 10.1A and 10.1B) by a rise, to be suggestive of a transient and sustained component of attention with differing temporal dynamics, as described in Nakayama and Mackeben (1989).

## Conclusions

We used an oddball paradigm to explore distortions in subjective time, under the assumption that observers orient or attend to a low-probability stimulus more than they do to a high-probability stimulus. The goal was to probe the objective temporal dynamics of temporal expansion as well as to determine whether the effect is truly attentional.

The data presented here support the traditional view (e.g. Creelman, 1962; Treisman, 1963; Thomas and Weaver, 1975) of time perception according to which perceived duration is a function of the amount of information processed per unit objective time, and also support the standard view that attention can influence the perception of duration (e.g. James, 1890;

Katz, 1906; Creelman, 1962; Treisman, 1963; Fraisse, 1963, 1984; Thomas and Brown, 1974; Thomas and Cantor 1975, 1978; Thomas and Weaver, 1975; Hicks, Miller, and Kinsbourne, 1976; Hicks et al., 1977; Brown, 1985; Mattes and Ulrich, 1998). According to the standard attentional model of time perception that has emerged through these papers, there is a 'counter' that keeps track of the number of units of temporal information processed for a given perceived event (Treisman, 1963; Thomas and Weaver, 1975). These models argue that some proportion of the units of temporal information is typically missed, especially when other tasks distract attention from monitoring the temporal markers. An increase of attention to the duration judgement itself results in fewer temporal cues being missed, therefore lengthening the apparent duration. These two factors account for the general pattern of reported distortions in the experience of duration.

However, the data described earlier (Tse et al., 2004) require a modification to the standard attentional model of time perception. Specifically, the engagement of attention by an unexpected event may not simply reduce missed information but actually increase the rate of information processing brought to bear on a stimulus. More units are detected during the event and it therefore seems to last longer, but this occurs because there are more units detected, not because fewer are missed. The previous hypothesis assumed that attention affected sensitivity, leading to fewer missed cues in a stream of constant rate. Alternatively, it could be that sensitivity remains unchanged by attention but the rate of information processing increases. These interpretations are not mutually exclusive. Both could contribute to distortions in perceived duration and both are compatible with the notion of a counter that measures the amount of information processed in order to calculate the duration of perceived events. For either reason, an attended stimulus may appear to last longer than a less attended stimulus that lasts the same objective duration. The data presented here do not distinguish between these possible mechanisms of enhanced information processing.

An increased rate of information processing might favour an 'early' view of attentional action, where, for example, sensory neurons actually increase their rate of firing when acted upon by neuronal circuitry that realizes attentional allocation. Conversely, increased sensitivity, but constant information processing rate, might predict that early neurons whose receptive fields lie within an attended region would not demonstrate a rate of firing above non-attended baseline. Of course, increased sensitivity in the form of lowered firing threshold would tend to make a neuron fire more than when threshold was not lowered, suggesting that the mechanism that increases sensitivity to processed information could be inextricably linked to the mechanism that increases the rate of firing and rate of information processed.

It may be impossible to establish beyond all doubt that temporal expansion is caused by attentional allocation, and not by some other process associated with the onset of an oddball. Nonetheless, four properties of the discussed data suggest that temporal expansion is indeed a result of attentional allocation to the oddball. First, temporal expansion does not begin until at least ~75–120ms after stimulus onset. This may be due to the time it takes attention to be allocated to a stimulus after its onset. Second, the temporal rise-dip-rise dynamics of temporal expansion are consistent with the summation of effects from transient and sustained components of attention. Third, approximately the same temporal dynamics are evident for both visual and auditory modalities (Figure 10.1A), suggesting that the mechanism that underlies temporal expansion is central rather than peripheral. Fourth, evidence that temporal expansion is central in origin was found in another experiment (Tse et al., 2004; experiment 7), not described here, where it was shown that the effect can be found with high-level category novelty rather than just image novelty. While none of these experiments can prove beyond a shadow of a doubt that temporal expansion is attentional in origin, the evidence strongly implicates an attentional account.

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The predictions of traditional counter-based theories (Creelman, 1962; Treisman, 1963; Thomas and Weaver, 1975) and the results described here can be accounted for within a simple unified model. In line with the standard counter-based models, duration information about an event is lost to the extent that one is not attending to that event. The data described here update the standard attentional model insofar as processing of duration information may also get a boost when one attends to a stimulus. This could account for the temporal dynamics of the oddball-induced expansion in subjective time reported here. Subjective time never gets 'out of sync' with objective time, despite its expansion and contraction, because the 'rate' of subjective time per unit objective time may be flexible, as diagrammed in Figure 10.3. It may speed up when one orients to an oddball, and may slow down to the extent that one is not attending to a stimulus. More than one unit of subjective time can occupy a single unit of objective time because a unit of subjective time is a function of the amount of perceptual information processed, and this amount can presumably vary per unit objective time. An oddball stimulus would then seem to last longer than a standard stimulus of equal objective duration because it triggers an increase in perceptual information processing.

This simple model allows us to make several predictions, which can be tested in the future. First, the degree of subjective temporal expansion should increase with the 'oddness' or improbability of an oddball (as long as the oddballs are all in the temporal expansion domain, i.e. longer in duration than ~150ms corresponding to the point where the curves cross zero in Figures 10.1A and B). For example, an oddball that occurs once every ten standards should appear to last longer than an oddball that occurs once every three standards. A corollary of this would be that an oddball can only be so 'odd,' since there is presumably an upper limit on how much and how long attention can boost information-processing resources above baseline, rooted ultimately in a physical limit, such as the maximum firing rate of neurons. Another prediction would be that stimuli that last longer than ~150ms should seem to last longer when they appear in unlikely rather than likely locations, contexts, or times. A related prediction is that temporal expansion should be enhanced by more salient oddballs. Indeed, the difference between the temporal expansion in experiments 1 and 2 is probably due to the fact that an expanding oddball is more salient than a stationary one. Another prediction is that temporal expansion should be triggered across
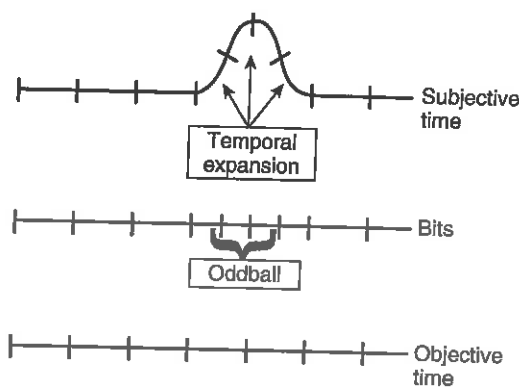


**Fig. 10.3** When an oddball occurs, more information is processed over the stimulus per unit objective time. If subjective time is gauged in terms of the amount of perceptual information processed, subjective time will seem to expand relative to objective time, as shown at the top of the figure, indicated 'temporal expansion'.

modalities, if it is a central attentional effect. For example, an unexpected and very loud noise should make a visual stimulus appear to last longer. This raises interesting questions. When temporal expansion occurs for a moving stimulus, it may seem to move 'in slow motion'. Indeed, temporal expansion may underlie the experience of slow motion during an attention-demanding event, such as skidding into the back of a car. But would temporal expansion in the visual domain lead to an analogue of slow motion in the auditory domain? Would, for example, pitches become deeper? Or would a given pitch just seem to last longer?

In unpublished data that is currently being collected in my lab we are checking for such cross-modal effects. So far we have found that a constant-tone sound standard does *not* seem to last longer or have a different pitch relative to other sound standards, when a visual stimulus with simultaneous onset and offset as the sound standards undergoes temporal expansion. All sound standards had the same onsets and offsets as visual standards and oddballs, and subjectively had the same duration even when one of them co-occurred with a visual oddball that underwent temporal expansion. Such 'splitting' of temporal expansion seems counterintuitive, because we think of time perception as subjectively unified. This raises the possibility that independent visual and auditory processes, attentional or otherwise, underlie temporal expansion in their respective domains. Still, this preliminary finding seems bizarre. How can two events, one auditory and the other visual, that start and stop at the same times, not feel like they have the same subjective duration? We are carrying out experiments to try to get to the root of this puzzle.

Finally, it is interesting to ask why we have evolved to experience events in a subjective time that can expand and contract relative to the presumed regular flow of objective time. One possibility is that just as attention can enhance the spatial acuity of the visual system (Nakayama and Mackeben, 1989; Mackeben and Nakayama, 1993; Shiu and Pashler, 1995) attention can also enhance the temporal resolution of visual processing (Correa and Nobre, 2008). Since heightened spatial or temporal resolution is presumably expensive, the visual system may only invoke heightened processing for stimuli of probable interest or importance. By making novel or important events run 'in slow motion' they may be processed in greater depth per unit objective time than 'normal' events, and afford greater consideration of possible courses of action than normally would be the case in the absence of temporal expansion.

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