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Retrospective and Prospective Timing: Memory, Attention, and Consciousness

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For millions of years, organisms have been products of evolution, gradually becoming increasingly adapted to their changing environments. Plants regulate their metabolism according to seasons, daily rhythms, and weather. Animals regulate their behaviour according to temporal constraints as well. Their nervous systems, down to at least planarians if not more simple organisms, have evolved to time events. However, only in the last several hundred years have humans consciously developed various external timing mechanisms, including four different kinds of chronometers (Roberts, 1998). This reflects the needs of humans for accurate timing that is not provided by natural mechanisms.

Relatively accurate timing of events and durations is essential to ensure the optimal functioning of organisms, who must have some way to remember the timing of past events and to anticipate the timing of future events. Organisms must encode temporal properties of important events, store representations of those properties, and use those representations for actions. For example, people must learn the temporal order of components of actions, such as getting dressed, making coffee, and driving a car. Such actions require that a person time durations to perform appropriate actions in the correct order and with the correct durations of components.

There are several qualitatively different kinds of temporal experiences: simultaneity, successiveness, temporal order, duration, and temporal perspective (Block, 1979, 1990). We mainly focus here on temporal order and duration judgements, especially in the range of seconds and minutes. Timing in this range is essential for representing present and past episodes. Duration timing is the most researched aspect of psychological time, probably because it is a complex and important aspect in terms of environmental adaptation. No single sensory organ or perceptual system subserves psychological time. Consequently, most theorists explain duration timing in terms of cognitive processes or interactions between cognitive and biological processes (such as involving biological clocks). Duration timing requires attention and memory, and the study of duration judgements reveals and clarifies the underlying cognitive processes (Block and Zakay, 1996; Zakay and Block, 1997).

TEMPORAL DATING: SERIAL POSITION AND RECENCY JUDGEMENTS

Cognitive evidence

Research investigating temporal dating judgements reveals some interesting and relevant conclusions. In one experiment (Hintzman and Block, 1971), participants were told to pay attention to a series of words for a later memory test. They were not forewarned that temporal dating would be required. After all words had been presented, participants were unexpectedly asked to judge the approximate serial (temporal) position of each word in the series. They were able to do so with considerable accuracy. Temporal information seems to be encoded in memory even under incidental conditions, and this process does not require the conscious intent to encode temporal information.

Several subsequent experiments clarified this finding. In one of them (Hintzman, Block, and Summers, 1973), participants viewed two separate series of words, again under incidental conditions. Afterwards, they were unexpectedly asked to judge whether each word had occurred in the first list or the second list, then to judge whether it had occurred near the beginning, middle, or end of the list. Again, participants were able to make these judgements with considerable accuracy. However, the errors that they made were particularly revealing. If a person incorrectly judged that a word had occurred in a particular list, the person nevertheless tended to judge that it had occurred in the correct part of the list. Thus, incorrect position judgements did not simply migrate to temporally adjacent locations. This finding suggests that participants based their position judgements on incidentally encoded contextual information instead of on hypothetical time tags that locate events on a continuous scale of absolute time. Alternative explanations are possible. For example, oscillators with different characteristic frequencies may separately encode within-list and between-list information (cf. G. D. A. Brown and Vousden, 1998). This kind of explanation is weakened by the findings of other studies, which show that people can remember contextual information that has no temporal basis even if they are not forewarned that they will be required to do so. In one such experiment, each word in a long series was presented either auditorily or visually, and people were subsequently able to remember the presentation modality of tested words with above-chance accuracy (Hintzman, Block, and Inskeep, 1972).

Additional supporting evidence comes from studies of autobiographical memory in which participants are asked to date personal memories of events that occurred during relatively long time periods, such as months and years. People can make such judgements with some accuracy. However, their judgements also reveal systematically biased inaccuracy, called *scale effects*: a person may show relatively good accuracy in dating an event as having occurred during a particular time of day but show considerable inaccuracy in remembering the day, month, or year during which the event occurred (Friedman and Wilkins, 1985). Friedman (1993; see also this volume, Ch. 5) interpreted this kind of evidence as supporting what he called *location-based* rather than *distance-based* processes. Location-based processes are those that involve judging the recency of an event in a way that is influenced by important contextual landmarks (Shum, 1998), whereas distance-based processes are those that involve judging recency in a more absolute way, such as in terms of the strength of a memory trace. Evidence for location-based processes suggests that relative contextual information, rather than absolute time tags or memory strength, subserves temporal memory judgements.

Evidence that contextual information is automatically encoded comes from two main sources. First, participants can make reasonably accurate temporal dating judgements without being forewarned that they will have to do so (Hintzman and Block, 1971). Second, some experimenters have compared incidental and intentional memory conditions, in which the latter involves informing participants in advance that they will be asked to remember the temporal location of events. These studies reveal that there is little or no greater accuracy in the intentional condition (Auday, Sullivan, and Cross, 1988; but see Jackson, 1990). In short, people automatically encode contextual information concerning experienced events, a process that does not require conscious intention. When they later need to make a temporal order or recency judgement, they rely on whatever information is available in memory to reflect the temporal dimension, and they use contextual information and logical inferences based on it.

Memory for the recency of an event is apparently not limited to humans. Scrub jays are able to remember how long ago they cached (stored for later use) certain food items, either wax-moth larvae or peanuts (Clayton and Dickinson, 1998, 1999). When the scrub jays were allowed to recover wax-moth larvae, which are their preferred food items, with only a short delay, they chose to recover them instead of peanuts. However, when they were not allowed to recover wax-moth larvae until after the larvae would have perished, the scrub jays instead chose to recover the non-perishable peanuts. Clayton and Dickinson argued that this evidence meets the criteria for episodic-like memory in nonhuman animals—that is, memory for spatial and other contextual associations to personally experienced events, which in this case was the act of caching the food items. As such, non-human animals may automatically encode contextual information along with other information about their own actions. When a subsequent temporal judgement becomes important and relevant, they may rely on this contextual information. The extent to which non-human animals use encoded contextual information is probably limited compared to the extent to which humans use encoded contextual information. Non-human animals probably cannot make logical inferences about temporal order, position, and duration.

Neuropsychological evidence

People with brain damage in the prefrontal cortex usually show relatively little impairment in remembering events. However, they have difficulty performing memory tasks that require temporal judgements. For example, they are seriously impaired in judging which of two remembered events occurred more recently (e.g. Milner, 1982; Milner, McAndrews, and Leonard, 1990; Petrides and Milner, 1982). This impairment of temporal memory occurs mainly if there is damage to the dorsolateral prefrontal cortex, specifically in and around Brodmann's area 46. In addition, encoding the temporal order of external events more heavily involves the right prefrontal cortex, whereas encoding the temporal order of internal events more heavily involves the left prefrontal cortex (see Milner, 1982).

Milner, McAndrews, and Leonard (1990) proposed two hypotheses concerning the role of the frontal lobes in temporal-order encoding: (1) 'If the frontal lobes parse and organize the temporal contexts of events, one outcome of such operations could be thought of as a direct encoding of temporal tags for events in memory' (1990: 991), and (2) the frontal lobes 'develop appropriate encoding and retrieval strategies for the reconstruction of temporal order' (1990: 992). Although they favoured the second hypothesis, the first hypothesis is also tenable, and the two functions are not mutually exclusive. Thus the dorsolateral prefrontal cortex may encode contextual information, thereby enabling a person subsequently to remember the order of recent events (Fuster, 1995, 1997). Because the prefrontal cortex is critically involved in control of behaviour across time, Moscovitch (1992) proposed calling the corresponding memory system *working with memory* rather than simply *working memory*. Some controversy remains concerning whether the prefrontal cortex subserves the encoding of both temporal and spatial context. Schacter (1987) proposed that the prefrontal cortex is implicated in both, whereas Lewis (1989) argued that the prefrontal cortex subserves the encoding of only temporal context. According to Lewis, the hippocampus plays a more important role in processing information about spatial context.

The role of the dorsolateral prefrontal cortex may also include timing short durations (experiencing duration in passing). In other words, it may contain specialized neural circuits that are part of an internal-clock mechanism which is necessary for judgement of durations in the range of seconds to minutes (for relevant discussion, see Block, 1996; Block and Zakay, 1996; Church, 1989; Rubia *et al.*, 1998). Nichelli *et al.* (1995) interpreted the decreased accuracy shown by patients with frontal lobe damage in terms of an impaired reference memory system for time intervals. Although the dorsolateral prefrontal cortex seems to be crucially involved in various temporal tasks, its exact role in these phenomena remains unclear (Nichelli, 1993).

The neurotransmitter dopamine is found throughout the prefrontal cortex. Some evidence suggests that the dopamine D1 receptor site plays an important role in working memory (Goldman-Rakic, 1992; Sawaguchi and Goldman-Rakic, 1991). Some drugs that influence prospective temporal judgements may influence D1 dopamine receptor sites in the dorsolateral prefrontal cortex. Dopamine agonists lengthen prospectively experienced duration (i.e. they increase the subjective time rate), whereas dopamine antagonists shorten prospectively experienced duration (Hicks, 1992).

McAndrews and Milner (1991) studied patients with damage to the medial temporal lobes (i.e. the hippocampus and adjacent structures). They presented a series of stimuli and then tested the patients' memory by presenting test stimuli in pairs and asking them to judge which of the two had occurred more recently. When the patients were able to remember both stimuli, they performed normally on the recency judgement task. Thus, although patients with medial temporal-lobe damage show deficits in encoding permanent episodic memories, when they are able to acquire and explicitly retrieve an episodic memory, they often can remember associated contextual information, which they may use to make temporal judgements about the events. As we noted earlier, frontal-lobe patients show roughly the opposite: impaired memory for temporal information but normal memory for event information. These findings suggest that the hippocampus and the dorsolateral prefrontal cortex may perform somewhat separate (but interrelated) functions. Schacter proposed 'that remembering of temporal order constitutes one component of episodic memory, subserved by the frontal regions, and that remembering of recently presented items constitutes another component of episodic memory, likely subserved by the medial temporal regions' (1989: 704). The dorsolateral prefrontal cortex may supply the hippocampus with information about the cognitive context of events, and the hippocampus may encode this information in association with information about the content of events. In a subsequent section, we discuss the role of medial temporal lobe structures in retrospective duration judgements.

DURATION JUDGEMENTS

We need to distinguish between two kinds of duration judgements: (1) judging the duration of a single event (i.e. a stimulus), and (2) judging the duration of a series of events (i.e. a time period). These two kinds of duration judgement almost certainly involve different processes, and failing to distinguish between them may lead to conclusions that seem to be, but are not actually, contradictory.

Research reveals that non-human animals can learn to make one response to a relatively short stimulus, such as a 2-second light flash, and another response to a relatively long stimulus, such as a 10-second light flash (e.g. Fetterman, 1995). People can remember the duration of each event (e.g. word) in a long series of events with some accuracy even if they are not forewarned that they will be asked to do so (Hintzman, 1970). Duration information is apparently encoded relatively automatically as an integral part of the experience of an event.

A substantially larger body of research has focused on processes involved in judging the duration of a series of events. In this case, duration is not an integral property of a single stimulus, and the processes involved in experiencing and remembering the duration of a series of events are probably relatively complex. In his famous chapter in *The Principles of Psychology*, James (1890) made an important distinction. He claimed that different variables influence the 'retrospective and prospective sense of time' (p. 624): the apparent magnitude of a past duration lengthens as a function of 'the multitudinousness of the memories which the time affords' (p. 624), whereas the apparent magnitude of a duration in passing lengthens when 'we grow attentive to the passage of time itself' (p. 626). Researchers have investigated James's claims by using two kinds of methodology. In one kind, participants prospectively expose stimuli at a rate of one per subjective second until stopped by the experimenter, and then they retrospectively estimate the total duration (e.g. Frankenhaeuser, 1959; Hicks, 1992). The typical finding is that the retrospective verbal (numerical) estimate is less than the total duration produced prospectively. However, this kind of experiment does not afford a valid comparison of prospective and retrospective timing, because the duration is judged with two different methods.

A better way to test James's claim is by comparing duration estimates in what researchers now call the *prospective paradigm* and the *retrospective paradigm*. In the prospective paradigm, participants know in advance that they will later be asked to judge the duration of a time period. In the retrospective paradigm, participants do not have this knowledge. In both cases, participants experience a time period containing the same external information and nominal processing task, if any. However, the way in which they experience the duration and the various cognitive processes involved may differ. In the prospective paradigm, a person may intentionally (effortfully) encode temporal information as an integral part of the experience of the time period. This is partly why Block (1990) and others have used the term *experienced duration* to refer to the prospective paradigm. In the retrospective paradigm, a person may automatically and incidentally encode contextual information and may later need to effortfully retrieve from memory whatever information is relevant. Hence, the term *remembered duration* refers to the retrospective paradigm.

Many researchers have used the prospective paradigm, but few have used the retrospective paradigm. The main reason is that after a person is asked to provide a retrospective judgement, the person becomes aware that he or she may be asked to judge a subsequent duration. This is the defining characteristic of prospective judgement. Gilliland, Hofeld, and Eckstrand (1946) questioned whether the duration judgement paradigm would influence a person's duration judgements, but they did not report any evidence. Bakan (1955) conducted the first experiment, but he found no significant difference in duration judgements. The issue lay dormant for twenty years. Investigations of the duration judgement paradigm did not become common until after Hicks, Miller, and Kinsbourne's (1976) seminal study. In this study, participants sorted playing cards according to a rule requiring the processing of either zero, one, or two bits of information per card. In the prospective paradigm, verbal estimates of the duration were an inverse linear function of the amount of information processed. In the retrospective paradigm, the amount of information processed did not influence duration judgements.

More convincing evidence that prospective and retrospective duration judgements involve somewhat different processes or systems comes from findings that several variables differentially influence judgements in the two paradigms. For example, Block (1992) replicated Hicks and colleagues' finding. In the first experiment, experienced duration decreased when a person performed a more difficult processing task, but remembered duration was not affected. In the second experiment, remembered duration increased when participants performed several

different kinds of tasks during the duration, but experienced duration was not affected. These findings reveal a double dissociation, thereby providing strong evidence that different processes or systems subserve the duration judgements in the two paradigms.

Most theorists have interpreted this kind of evidence as supporting a distinction between processes subserving prospective and retrospective judgements (e.g. Block, 1992; Hicks, Miller, and Kinsbourne, 1976). However, some theorists have emphasized the essential similarity of the timing processes involved. For example, S. W. Brown concluded that 'the most important feature of [his] results is the similarity of prospective and retrospective judgments' (1985: 119). This statement is striking, especially because he found that prospective judgements were greater in magnitude and more accurate than retrospective judgements.

Cognitive variables, such as task difficulty, greatly influence judgements of short durations. In attempts to explain this pervasive kind of finding, theorists have proposed various cognitive models of psychological time. Psychological time depends on complex interactions among the various conditions under which a duration is experienced and the context at the time the person makes a duration judgement (Block, 1989). Perhaps the most important factor is the time estimation paradigm; differences between prospective and retrospective timing are becoming clear (Block and Zakay, 1997). Under retrospective conditions, participants must construct a duration judgement from the contextual changes that were automatically encoded in memory during a time period. Under prospective conditions, this automatic encoding of context also occurs, but it plays a relatively minor role. The reason is that under prospective timing conditions participants effortfully attend to time during a duration and thereby accumulate relevant temporal information. This information is the most salient information at the time the person judges the duration. In short, different cognitive processes underlie prospective and retrospective judgements of duration.

Outside the laboratory, it may sometimes be difficult to tell whether any particular time estimate is being made primarily prospectively or retrospectively, and it may also be difficult to tell whether some behaviours involve time at all. In some cases, however, it is clear that a temporal judgement must be made retrospectively. Consider research in which a person is asked to temporally date (i.e. judge the recency of) many past events that he or she experienced. A person can usually do so with at least some accuracy. These judgements are similar to retrospective duration judgements if one considers each time period to have begun when a person experienced an event and to have ended at the time the recency judgement was made. It would be nearly impossible for a person to have been prospectively attending to the duration of each of these time periods, because the ending point of each time period is arbitrary. Further, when a person is asked (under prospective conditions) to track the duration of several concurrent events, accuracy of timing decreases if the person has more events to track (S. W. Brown, 1997).

RETROSPECTIVE DURATION JUDGEMENTS

Cognitive evidence

Theorists typically propose memory-based models of remembered duration. Specific theories focus on stored and retrieved information, or 'storage size' (Ornstein, 1969); remembered changes (Fraisse, 1963); encoded and retrieved contextual changes (Block and Reed, 1978); or interval segmentation (Poynter, 1983). Most theorists ignore the role of a person's attention to time unless there is little information to process, there are frequent feelings of boredom, or there are other conditions that arouse a temporal motive (Doob, 1971). Memory-based explanations, which do not involve attention to time *per se*, are more typically needed. To the extent that a person can retrieve a greater number of events, he or she remembers the duration of a time period as being longer (Ornstein, 1969). However, retrospective duration judgements are not simply based on the degree of recallability of individual events (Block, 1974; Block and Reed, 1978); other factors are involved. Even if people use this strategy, they do not attempt to retrieve all available memories of events from the time period. Instead, they may rely on an availability heuristic in which they remember a duration as being longer to the extent that they can easily retrieve some of the events that occurred during the time period.

Changes in cognitive context have a more important influence on remembered duration than does the number of stimulus events encoded and retrieved. Contextual changes may occur as a result of variation in environment stimuli, interoceptive stimuli, and the processing context. Block and Reed (1978) found that people remembered a time period as being longer in duration to the extent that there were greater process context changes. These are changes that occur when a person employs different kinds of cognitive processes to encode information. For example, a time period containing some words that required structural processing and other words that required semantic processing was remembered as being longer in duration than an equal time period containing words that only required structural processing or only required semantic processing. Memory for individual words was best in the semantic-only condition, intermediate in the mixed-processing condition, and worst in the structural-only condition. Taken together, these findings lead to the rejection of simple event-memory explanations of remembered duration, such as Ornstein's (1969) storage-size model. Block (1982) investigated environmental context as another salient source of contextual changes. A person's previous experience in a particular environment shortened the remembered duration of a subsequent time period spent in it. Poynter (1989; see also Zakay *et al.*, 1994) found that remembered duration is longer to the extent that a to-be-estimated interval is segmented by high-priority events which attract attention (like politicians' names inserted among names of furniture). Segmentation, however, may be interpreted to be a particular case of contextual changes created as a result of the appearance of the high-priority events.

A contextual-change model predicts a positive time-order effect in remembered duration, especially if relatively long time periods and a comparative duration-judgement task are used. A positive time-order effect is the finding that a person will usually remember the first of two equivalent time periods as being longer than the second (Block, 1982, 1985). More generally, a positive time-order effect is revealed when a person makes longer judgements of durations presented earlier in a series of several durations (see, for example, S. W. Brown and Stubbs, 1988). According to a contextual-change model, a person encodes a greater number of changes in contextual elements during a more novel experience, such as during the first of several durations. Two additional findings support the notion that contextual changes underlie the positive time-order effect. The effect is eliminated if the environmental context prevailing during the second of two durations is different from that prevailing during the first (Block, 1982). It is also eliminated if changes in emotional context that would ordinarily occur during the first duration occur instead during a preceding time period (Block, 1986). Note that the positive time-order effect is somewhat counter-intuitive. Ornstein's storage-size model predicts the opposite, a negative time-order effect attributable to 'items dropping out of storage' (1969: 107). In fact, some of Ornstein's data reveal a positive time-order effect rather than a negative time-order effect.

To the extent that the first of two time periods becomes relatively less recent and the second becomes relatively more recent (i.e. the interval between the two increases), a person may have relatively more difficulty remembering the contextual changes that occurred during the first time period. In such a case, the typical positive time-order effect may reverse, becoming a negative time-order effect. Wearden and Ferrara (1993), who used two brief stimuli and asked people to judge the relative duration of the two, obtained such evidence. They called it a *subjective shortening* effect.

It is nearly impossible to find evidence revealing that non-human animals can make retrospective duration judgements. There are at least two possible explanations for why this is the case. One possibility is that researchers have not attempted to devise conditions testing animals' abilities to make retrospective duration judgements. Although such testing is difficult, it is possible. It requires subsequently using differential reinforcement of at least two responses, one indicating one kind of duration judgement regarding a previously presented time period (e.g. 'shorter in duration') and another indicating a second kind of temporal judgement (e.g. 'longer in duration'). The main problem may be devising a way to present test stimuli, because each stimulus would have to symbolize a previously experienced time period. Another possibility is that animals do not encode temporal information unless they experience a stimulus or a time period under prospective conditions. Compared to prospective timing, retrospective timing may involve evolutionarily more complex processes, perhaps because it has not been essential to the survival and subsequent reproduction of organisms.

Neuropsychological evidence

The long-term encoding of episodic memories requires the intact functioning of medial temporal lobe structures, especially the hippocampus, apparently working in conjunction with information supplied by the prefrontal cortex. Medial temporal lobe structures are also involved in judgements of the duration of past time periods. Patients with damage to the medial temporal lobes, especially the hippocampus, show abnormally short reproductions of durations greater than about 5–15 seconds (Richards, 1973; Williams, Medwedeff, and Haban, 1989). The prefrontal cortex and the hippocampus are intimately connected and apparently play a conjoint role in the processing of working memory and episodic-memory information (Goldman-Rakic, Selemon, and Schwartz, 1984; Olton, 1989). The working memory system of the prefrontal cortex apparently generates encodings of contextual information, which a person may use to make various temporal memory judgements. Temporal memory judgements concerning past events and episodes depend on retrieving encoded contextual changes, including changes in process context, environmental context, emotional context, and other contextual associations (Block, 1982, 1986, 1992; Block and Reed, 1978). To the extent that retrospective order, recency, duration, and other similar temporal judgements rely on event information no longer represented in the working memory system, these kinds of judgements also require the hippocampus for the permanent encoding of events and associated contextual information.

The frontal lobes may also subserve a person's ability to organize various strategic processes required for retrieval of information from memory (Mangels *et al.*, 1996; Moscovitch and Melo, 1997; see also Friedman, Ch. 5, this volume). This function may be somewhat different from that involved in generating contextual information, although evidence on that issue is unclear.

PROSPECTIVE DURATION JUDGEMENTS

Cognitive evidence

Attention-demanding processes that occur concurrently with the processing of non-temporal (task) information influence prospective duration timing. Diverse research has revealed that experienced duration typically increases if the number of stimuli requiring processing is small, if a processing task is easy, or if participants do not need to respond actively to stimulus information (Hicks, Miller, and Kinsbourne, 1976; Zakay, 1993; Zakay and Block, 1997). Thus prospective timing is a dual-task condition in which attention must be shared between temporal and non-temporal information processing. Attending to time requires access to some of the same resources that non-temporal tasks do. For this reason, most theorists propose attention-based models of experienced duration (Block and Zakay, 1996; S. W. Brown, 1998; Macar, Grondin, and Casini, 1994; Thomas and Weaver, 1975; Zakay and Block, 1996). In these models, experienced duration increases to the extent that a person allocates more attentional resources to processing temporal information.

Evidence supporting attentional models comes from studies that have used a dual-task paradigm (S. W. Brown, 1997; Macar, Grondin, and Casini, 1994). If a person receives instructions on how much attention to allocate for stimulus information processing and how much to allocate for temporal information processing, prospective duration judgements are a function of the latter. For example, Zakay (1998) used a primary–secondary task paradigm. The magnitude of prospective duration judgements increased when participants were told that a temporal task was the primary task and that a simultaneous non-temporal task was the secondary task. The magnitude of the duration judgements decreased when the instructions were reversed. Zakay (1992) used another kind of experimental manipulation, in which a stimulus that attracted attention was presented during some intervals that required an ongoing temporal judgement. On those trials, the magnitude of the prospective duration judgement decreased.

In making a prospective duration judgement, a person compares the accumulated temporal units with the typical number of such units stored during reference durations. In the attentional-gate model (Zakay and Block, 1996, 1997), for example, the pulse count accumulated during the duration is compared to those stored in reference memory. This is a long-term memory store containing learned pulse counts, as well as (in the case of humans) translations of these total pulse counts into verbal (numerical) units. Some of these total pulse counts may originally have been stored in a retrospective way. For example, a person who encounters a certain traffic (stop) light repeatedly may initially encode the duration retrospectively. Later, the person may attend to time in a prospective way, storing additional pulse totals for this particular duration. As the person acquires expertise with a particular duration, his or her duration estimates presumably become more accurate and less variable (Zakay and Block, 1999).

Animals such as rats may be trained on a fixed-interval schedule, in which the animal is reinforced for the first response made after a fixed duration since the previously reinforced response (see Church, 1989, for a review). Research on animal timing more often uses a variant of this called the *peak procedure*, in which randomly interspersed discrete trials contain either fixed-interval reinforcement or no reinforcement at the usual time. A fixed-interval schedule essentially entails what is called the *method of production* in human research, in which a person is told to respond at the end of some previously defined duration (e.g. 'Say stop when you think that 30 seconds has elapsed'). As such, this schedule is by definition an example of the prospective paradigm. Animal researchers have typically had no need to propose an attentional mechanism, and they have not done much relevant research that might have revealed it. Do animals' prospective duration judgements show the same sort of attentional effects as those of humans? Research to date has left that important question unanswered.

Neuropsychological evidence

As we noted earlier, a working-memory system that is apparently subserved by the dorsolateral prefrontal cortex appears to play a role in the experience of time in passing. Short-duration judgements as well as subsequent recency and temporal-order judgements presumably require the functioning of this system. Prospective timing may also require a biological-clock mechanism. Scalar timing theory proposes that this mechanism consists of a pacemaker (which produces pulses), a switch, and an accumulator, with a comparison made between pulse totals in working memory and in reference memory (Church, 1984, 1989). Although scalar timing theory proposes a single mechanism, several partially dissociable brain systems may be involved in prospective duration judgements (Block, 1996).

Payk (1977) reviewed various case studies of what has come to be called the *Zeitrafferphänomen*, or *accelerated time phenomenon.* (A Zeitraffer is a mechanical apparatus to accelerate the apparent motion in a film, as in time-lapse cinematography, so common translations of *Zeitrafferphänomen* usually focus on accelerated motion of events or accelerated experience of time.) Binkofski and Block (1996) described a Zeitraffer patient (B.W.) with damage in his left-hemisphere prefrontal cortex resulting from a glioblastoma. The onset of his symptoms was surprisingly sudden: As B.W. was driving his automobile, he noticed that external objects seemed to be rushing towards him at an unusually fast rate. He stopped his car, unable to drive. He later described his experience as that of an 'accelerated motion' of events, and he complained that he could not even watch television because the progression of events was too quick for him to follow. When B.W. was asked to produce 60-second durations, his productions were greatly lengthened, averaging 286 seconds. (He made these productions under conditions of minimal environmental stimulation.) This evidence converges with B.W.'s description of his condition. He experienced events in much the way a normal person would experience events on a video-cassette recording being played on 'fast forward' (i.e. occurring at approximately six times their normal rate). Binkofski and Block concluded that the most likely explanation for these data was that the pacemaker component of B.W.'s internal clock was now producing pulses at a considerably decreased rate (see also Nichelli, 1993).

Researchers who have administered drugs to animals trained on fixed-interval schedules suggest that the internal clock may be subserved by dopaminergic neurons, which the prefrontal cortex is known to contain. The internal clock may also involve older brain areas such as the basal ganglia (Meck, 1996).

Brain areas that subserve the internal-clock mechanism may be separate from, but interconnected with, other areas that subserve the proposed role of attentional processes in prospective duration judgement. It is unclear which areas of the brain may subserve attention to time, a process that is implicated in research using the prospective paradigm. Studies using positron emission tomography suggest that several anatomically separate brain areas, including the thalamus, the parietal lobes, and the anterior cingulate gyrus, are involved in various aspects of attentionally guided task performance (for a review, see Posner and Raichle, 1994). These areas may also play somewhat different roles. The likely candidate for an area that subserves the allocation of attention to external events or to time is the anterior cingulate cortex. This area, located in an evolutionarily new part of the brain, may be the essential component of an executive attention network that directly influences the working-memory functions of the dorsolateral prefrontal cortex. As such, it may subserve the role of attention in the prospective timing of stimuli and durations.

Our conclusions about the likely roles of various brain areas in subserving prospective duration judgements differ from those of Kesner (1998). Kesner concluded that people with damage to the prefrontal cortex are not impaired on a task requiring short-term memory for the duration of a stimulus, but people with damage to the hippocampus are impaired on such a task. Perhaps the contradiction is more apparent than real: as we noted earlier, memory for the duration of an event and memory for the duration of a series of events may entail different processes. Additional research is needed, however, to clarify the roles of the anterior cingulate cortex, the dorsolateral prefrontal cortex, and the hippocampus in various kinds of tasks requiring temporal judgements.

DIRECTIONS FOR FUTURE RESEARCH

Research on various kinds of prospective and retrospective temporal judgements is needed to identify all the variables that influence them. Nevertheless, three issues call for special attention by time researchers:

1. In what ways do various kinds of temporal judgements involve similar processes and in what ways do they involve different processes? In particular, how are temporal dating judgements (e.g. recency, temporal location, and temporal order judgements) related to duration judgements? How are judgements of the duration of an event related to judgements of the duration of a series of events? Answering these questions requires an integration of cognitive and neuropsychological research.

2. Is it possible to create a unified model of prospective and retrospective duration judgements? Evidence strongly suggests that these two kinds of duration judgements rely on somewhat different processes (Block and Zakay, 1997). Nevertheless, it may be possible to combine the two kinds of judgement in a unified model.

3. Is human temporal cognition simply an elaborated version of temporal mechanisms that evolved during the course of evolution, or is it based on principles different from those that characterize non-human animals' temporal processes? This issue is related to the need to identify brain areas and mechanisms that subserve temporal processes in general and duration judgements in particular.

SUMMARY AND CONCLUSIONS

Relatively accurate timing of events and durations is essential to ensure the optimal functioning of organisms. Several kinds of temporal judgements, such as order, recency, and even recognition memory judgements, can be made retrospectively, based mainly on contextual information. The relevant information is encoded relatively automatically, as revealed by studies in which participants do not know that temporal information will be needed later (incidental memory). Evolutionarily newer cortical areas (e.g. dorsolateral prefrontal cortex, parahippocampal cortex, and hippocampus) apparently subserve this relatively automatic encoding of contextual information. Evidence indicates that duration judgements depend on several variables, most importantly the duration-judgement paradigm—that is, whether the judgement is made retrospectively or prospectively. Although it may sometimes be difficult to tell whether any naturally occurring duration judgement is retrospective or prospective, prospective judgements may ordinarily be more common. Retrospective duration judgements depend on the relatively automatic encoding of event and associated contextual information, which is retrieved in a controlled (non-automatic) way. In contrast, some temporal judgements are made prospectively—that is, in situations in which a person is aware that temporal information is needed, either immediately or later. Although the same contextual information may be encoded as in a retrospective paradigm, other information is also encoded. This information is encoded only in a deliberate (controlled) way, involving attention and hence more complete involvement of mechanisms of consciousness. Attending to temporal information apparently competes for the same pool of attentional resources as does attending to nontemporal information. Evidence suggests the additional involvement of evolutionarily older subcortical (and some newer cortical structures) in prospective situations.

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