ACTA NEUROBIOLOGIAE EXPERIMENTALIS

Acta Neurobiol Exp 2004, 64: 319-328

Prospective and retrospective duration judgments: an executive-control perspective

Dan Zakay[1] and **Richard A. Block**[2]

[1]Department of Psychology, Tel Aviv University, Ramat-Aviv 69978, Israel;
[2]Department of Psychology, Montana State University, Bozeman, MT 59717-3440, USA

Review

Abstract. Most theorists propose that when a person is aware that a duration judgment must be made (prospective paradigm), experienced duration depends on attention to temporal information, which competes with attention to nontemporal information. When a person is not aware that a duration judgment must be made until later (retrospective paradigm), remembered duration depends on incidental memory for temporal information. In the present article we describe two experiments in which durations involved with high-level, executive-control functions were judged either prospectively or retrospectively. In one experiment, the executive function involved resolving syntactic ambiguity in reading. In another experiment, it involved controlling the switching between tasks. In both experiments, there was a unique cost to the operation of control high-level, executive functions which was manifested by prospective reproductions shortening a finding that supports an attentional model of prospective timing. In addition, activation of executive functions produced contextual changes that were encoded in memory and resulted in longer retrospective reproductions, a finding that supports a contextual-change model of retrospective timing. Thus, different cognitive processes underlie prospective and retrospective timing. Recent findings obtained by some brain researchers also support these conclusions.

The correspondence should be addressed to D. Zakay, Email: dzakay@post.tau.ac.il

Key words: attentional-gate, executive functions, prospective timing, retrospective timing

PROSPECTIVE AND RETROSPECTIVE DURATION JUDGMENTS: AN EXECUTIVE-CONTROL PERSPECTIVE

A person may make a duration judgment under either of two instructional conditions. The prospective paradigm is defined as a situation in which a person is aware, during a time period, that he or she needs to estimate its duration. Because of this awareness, Block (1990) referred to a duration judgment using this paradigm as one assessing experienced duration. In the retrospective paradigm, a person becomes aware of the need to judge a duration only after it has ended. In this paradigm, a duration judgment must rely mainly on information retrieved from memory. For this reason, Block referred to this paradigm as one assessing remembered duration.

Some theorists (e.g., Brown and Stubbs 1992) have claimed that prospective and retrospective duration judgments involve similar cognitive processes, but other researchers have argued that different cognitive processes subserve experienced and remembered duration (Block 1990, 1992, Hicks et al. 1976, Zakay 1989, Zakay and Fallach 1984). This argument was supported by a meta-analytic review (Block and Zakay 1997), in which it was found that some variables differentially influence prospective and retrospective duration judgments.

EXPERIENCED DURATION

Prospective duration timing depends on attention-demanding processes that occur concurrently with the processing of nontemporal information (Pouthas and Perbal 2004 – this issue). Thus, prospective timing is a dual-task condition: a person must divide attention between temporal and nontemporal information processing, and attending to time requires access to some of the same resources that nontemporal tasks use. For this reason, models of experienced duration usually emphasize attention (Block and Zakay 1996, Brown 1997, Macar et al. 1994, Zakay 1993a, Zakay and Block 1996). These models often assume that signals reflecting the passage of time are accumulated in a cognitive counter (Wearden 2004 – this issue). If a person focuses more attention on temporal information processing, more time signals are processed. To the extent that a concurrent nontemporal task is more demanding, a person has fewer attentional resources available to allocate to temporal information processing, and fewer time signals accumulate in the cognitive counter. Prospective duration judgments are a function of the total number of accumulated time signals.

Block and Zakay (1997) concluded that experienced duration decreases as the difficulty of the nontemporal information-processing task increases. This conclusion is supported by several experiments. Zakay and Fallach (1984 (Experiment 3)) used either an easy or a difficult Stroop (1935) task and found that prospective estimates made immediately after a duration increased if the processing task was easier, whereas retrospective estimates were unaffected by processing difficulty. Using a different kind of task, Block (1992 (Experiment 1)) conceptually replicated Zakay and Fallach's findings. Another common finding predicted by an attentional model is that if a more complex stimulus or stimulus sequence occurs during the time period, experienced duration decreases (e.g., Macar 1996). It can be concluded that an attentional model of experienced duration has received considerable support, although more research is needed to further validate the model.

REMEMBERED DURATION

Unless a task is easy or boring, a person usually does not attend to time very often under retrospective conditions. Models of retrospective timing therefore usually emphasize memory (e.g., Block 1990, Fraisse 1963, Ornstein 1969, Poynter 1983). Ornstein's (1969) storage size hypothesis is one of the more durable models of remembered duration. He proposed that remembered duration is a function of the amount of memory storage space for events that occurred during an interval. Support for this model, mostly from studies investigating effects of number of stimuli and their complexity, has been inconsistent (e.g., Block 1974, 1978). The contextual-change model is an alternative memory-based model (Block 1989, 1990, Block and Reed 1978). It proposes that remembered duration is a cognitive construction based on the availability of contextual changes encoded in memory during the time period. These changes occur in emotional, environmental, and other contextual elements. If more contextual changes are available for retrieval, remembered duration increases.

Many researchers have investigated effects of stimulus complexity on remembered duration. If a time period contains more complex stimuli, remembered duration sometimes increases (e.g., Ornstein 1969 (Experiment 2)).

However, past findings are inconsistent. Block and Zakay (1997) found insufficient evidence that stimulus complexity has an effect. Information-processing difficulty, the major variable that affects prospective judgments, seems to have little or no influence on retrospective judgments (Block and Zakay 1996). Instead, evidence suggests that other variables influence remembered duration and that these do not usually influence experienced duration. For example, Block (Block 1992 (Experiment 2), Block and Reed 1978 (Experiment 2)) found that if a person must change the way he or she processes information, remembered duration increases, but experienced duration is not affected. Zakay and colleagues (1994) found that segmentation of information affects retrospective timing but not prospective timing. It is essential to find more such double dissociations to support the conclusion that at least partially different cognitive processes subserve prospective and retrospective duration judgments.

DURATION JUDGMENTS AND MENTAL LOAD

There is an intimate link between attentional processes and prospective duration judgments (Zakay 1998, Zakay and Block 1997). Thus, Zakay and co-workers (1999) hypothesized that prospective duration judgments, but not retrospective judgments, can be used as a measure of the amount of mental load required for the performance of a nontemporal task. Zakay and Shub (1998) demonstrated the suitability of prospective duration estimation to serve as a secondary task for workload measurement. In one experiment, participants performed either a Stroop task or a card-sorting task with two levels of difficulty. While performing these tasks, participants were also engaged in either a duration-production or a duration-estimation task. Participants in a control group performed the nontemporal tasks without the timing tasks. All participants also rated the level of workload associated with performance of these tasks. Produced durations were highly correlated with subjective workload ratings and with performance indices. Similar findings were obtained in a flight simulation conducted by pilots. Again, produced durations were sensitive to concurrent workload levels associated with flight performance and were correlated with subjective ratings of workload.

Note that there is an inverse relationship between duration judgments obtained using the method of production and those obtained using the method of verbal estimation or the method of reproduction: Increased workload lengthens prospective productions, but it shortens prospective verbal estimates and reproductions (Zakay and Block 1996). In addition, greater workload may also lead to an increase in the variability of duration judgments (Brown 1997).

The sensitivity of prospective duration judgments to attentional demands has also been used to resolve issues concerning automatic and intentional encoding processes in face encoding. Block and colleagues (2000) found that prospective timing is not affected by a concurrent face-encoding task, and they inferred that encoding faces per se is at least partly automatic. On the other hand, Block and colleagues (2003) found that encoding external features of faces (e.g., eyeglasses) interferes with prospective timing, which indicates that this feature-encoding process is not entirely automatic. These findings support the view that temporal paradigm is a useful secondary task to assess attentional interference effects.

DURATION JUDGMENTS AND MENTAL LOAD ASSOCIATED WITH EXECUTIVE FUNCTIONS

The findings described in the previous sections support the notion that different cognitive processes underlie retrospective and prospective duration judgments. However, all the empirical findings were obtained in regard to mainly nonexecutive functions and information-processing tasks. Contemporary research in cognitive psychology increasingly emphasizes questions pertaining to the regulatory processes underlying supervisory control functions (Gopher 1993, 1996, Meiran 1996, Meyer and Kieras 1997). Some of these questions concern the processes and mechanisms by which intentions are translated into goal-directed behavior and govern its conduct. Researchers who focus on these control processes also investigate the operational costs of control activities to the human information-processing system (Gopher et al. 2000).

The need to study executive-control functions separate from nonexecutive functions is supported by findings revealing functional and anatomical separation between the executive-control system and other processing systems that perform operations on specific inputs (Posner and Peterson 1990, Posner et al. 1988). Several researchers (e.g., Meyer and Kieras 1997, Shallice 1994) have introduced different views about the architecture of the executive-control system.

Baddeley and Hitch (1994) viewed executive control as the operational component of working memory. This mechanism coordinates information from several slave systems, each of which is responsible for processing a different kind of information. Brown (1997) suggested that prospective duration judgments consume resources associated with the executive control of working memory. Thus, it is natural to assume that prospective duration judgments are sensitive not only to attentional demands of nonexecutive information-processing tasks, but also to demands of high-level, executive-control functions. It is also expected that to the extent that the operation of executive functions is encoded in memory, this will be reflected in the magnitude of retrospective duration judgments. In any case, the impact of executive-control functions on prospective and retrospective duration judgments should yield a double dissociation similar in its pattern to that revealed by nonexecutive cognitive tasks. Obtaining the expected double dissociation in tasks requiring executive-control functions would strengthen the support for the notion that different cognitive processes underlie the two duration-judgment paradigms.

In the following sections, we describe two experiments testing the impact of high-level, executive-control functions on duration timing.

IMPACT OF SYNTACTIC AMBIGUITY ON PROSPECTIVE AND RETROSPECTIVE DURATION JUDGMENTS

Along with language production, reading is one of the most important cognitive functions that differentiate humans from other organisms. When people read a sentence (for example, when you, the reader, read this sentence), it seems to be mainly an automatic and effortless activity. However, reading is a complex activity. Without syntax, reading would become an almost impossible and chaotic process. Just and Carpenter (1987) said that "Syntax helps a reader decode a linear string of words into a more complex, interrelated structure. The syntactic organization helps to hold the words of a sentence together in working memory in their appropriate groupings while the meaning of the sentence is being processed" (p. 165).

Readers of all ages have to allocate and divide attentional resources between different cognitive processes involved in reading a word, sentence, and discourse levels (Stine-Marrow et al. 1996). The higher the complexity of a sentence, or of the reading task, the greater the depth of processing the reader is required to perform (Craik and Tulving 1975). Mistler-Lachman (1975) reported that the depth of required processing increases if a reader has to process ambiguous sentences, and when the ambiguity is syntactic the required depth of processing is the greatest. When a reader faces syntactic ambiguity, high-level control processes intervene in the reading process, and the reader experiences the need to invest mental effort in the process.

Syntactic ambiguity (SA) exists when a sentence has several possible syntactic analyses. An example is the sentence, "Time flies like an arrow" (Just and Carpenter 1987). At least several main syntactic interpretations are possible: (i) "Time passes as quickly as an arrow does"; (ii) "I order you to time those flies as you would time an arrow"; (iii) "I order you to time flies as an arrow would time flies"; and (iv) "Certain flies called "time flies" are fond of an arrow". Just and Carpenter suggested that readers deal with SA as follows: (i) they compute the multiple interpretations of a sentence; but (ii) they choose the more likely syntactic interpretation on the basis of context and relative frequency of occurrence, and discard the alternative interpretations; and (iii) they mark that point in their representations of the sentence as a choice point. This description clearly indicates that executive-control functions are involved in the process of resolving SA. There is a need to initiate memory search, to inhibit responses, and to encode high-level structures (i.e., a choice point) in memory. Inhibiting responses and encoding high-level structures is also illustrated by the way people comprehend the sentence, "Time flies like an arrow and fruit flies like a banana" (a sentence attributed to the linguist Susumu Kuno and popularized by the comedian Groucho Marx).

If resolving SA involves executive-control functions, and if the activation of such processes consumes attentional resources, prospective duration judgments should be sensitive to this: prospective reproductions should be shorter if there is SA than if there is no SA. Even though prospective reproductions are usually longer than retrospective reproductions (Block and Zakay 1997), prospective reproductions of sentences with SA may be shorter than retrospective reproductions of sentences without SA.

SA should not affect retrospective reproductions, which are not sensitive to the amount of attentional resources allocated for timing. However, resolving SA requires shifting among potential interpretations, and this process should increase the number of contextual changes encoded or the degree of segmentation in episodic memory structures. Information about the choice point is also encoded. Thus, it is predicted that retrospective reproductions of durations during which SA was encountered should be longer than reproductions of durations during which SA was not encountered.

Zakay and Block (unpublished results) tested these hypotheses. A total of 40 undergraduate students were tested individually. They were told that the experiment concerned reading styles, and they were asked to read a series of sentences. Each participant was randomly assigned to one of four experimental conditions formed by the orthogonal combination of temporal paradigm (retrospective vs. prospective) and reading task (SA vs. no SA). In the retrospective condition, time was not mentioned; in the prospective condition, participants were told that after the reading was completed they would be asked to reproduce the total reading duration. Reading duration was measured for each participant without his or her knowledge. Upon completing the reading, participants were asked to reproduce the reading duration by pressing a button. After the reproduction was terminated, participants rated the degree of mental load they experienced while performing the reading task. A 10-point scale was used for the rating, with 1 designated "no feeling of mental load" and 10 labeled "extreme feeling of mental load."

In the SA condition, six ambiguous English sentences were presented. Two examples of SA sentences are: (i) "Since Jay always jogs a mile seems a short distance to him" – the ambiguity is caused by the omission of the comma, which can create different meanings if it is put after "jogs" or after "a mile"; (ii) "The horse galloped fast after the race his legs always shiver" – the ambiguity is caused by the omission of the period, which can create different meanings if it is put after "fast" or after "race".

In the control condition, the same sentences were presented with punctuation marks, so that each sentence had only one meaning. The results of the experiment are presented in Table I.

In result, reading duration was significantly longer if there was SA than if there was no SA, and this effect did not interact with duration-judgment paradigm. Ratings of mental load were significantly higher if there was SA than if there was no SA. If there was no SA, ratings of mental load were significantly higher in the prospective than in the retrospective duration-judgment paradigm. If there was no SA, ratings of mental load did not differ between the two paradigms. In all conditions, reproductions were significantly shorter than actual reading durations, presumably because all participants were attending to time during the reproduction, and there was no concurrent nontemporal task to perform. If there was no SA, prospective reproductions were significantly longer than retrospective reproductions. The duration-judgment ratio, which is the ratio of the reproduced duration to the reading duration, was also significantly larger in the prospective paradigm than in the retrospective paradigm. On the other hand, if there was SA, retrospective reproductions were significantly longer than prospective reproductions. The duration-judgment ratio was also greater in the retrospective than in the prospective paradigm.

Thus, the findings obtained in the experiment confirmed the predictions. The decrease in prospective reproductions in the SA condition in comparison to the simple reading (no-SA) condition indicates that resolving SA is a process that consumes attentional resources. The increase in retrospective reproductions in the SA

Table I

Syntactic ambiguity experiment – results

	Retrospective Condition				Prospective Condition			
Syntactic Ambiguity	RD	REP	DJR	LOAD	RD	REP	DJR	LOAD
Yes	46.86	37.29	0.79	4.80	49.91	24.30	0.48	4.70
No	36.98	26.59	0.71	2.30	39.09	32.68	0.83	3.00

(RD) reading duration (in seconds); (REP) reproduced duration (in seconds); (DJR) duration judgment ratio (REP/RD); (LOAD) mental load rating (on a 10-point scale) condition in comparison to the no-SA condition indicates that resolving SA is a process that produces contextual changes that are encoded in memory. This finding is in line with theories about the process of resolving SA (cf. Just and Carpenter 1987).

Overall, the pattern of results reveals a double dissociation between prospective and retrospective duration judgments in terms of how they are affected by the high-level process of resolving SA.

IMPACT OF TASK SWITCHING ON PROSPECTIVE AND RETROSPECTIVE JUDGMENTS

The task-switching paradigm provides another methodology for the study of executive-control processes, and it is also one of the most frequent and robust manipulations of executive control (Shallice 1994). In the task-switching paradigm, participants are required to change between two or more ways of processing information when responding to sequences of stimulus presentations (Gopher et al. 2000). Each switch involves activities such as inhibition of responses to the previous task, selection and activation of new intentions and schemata, and sequencing operations in time. Gopher et al. suggested that the main interest concerns the difference in the performance of a task on trial *n*, when participants perform the same task or a different task on trial *n*–1. This difference reflects the costs of switching.

Switching between tasks and mental sets is common in everyday situations. Indeed, the task-switching paradigm has been used in many experiments, and the results show significant transition costs that are linked to the first trial after a switch, costs which are not part of the cost associated with the regular performance of each task (e.g., Gopher et al. 2000, Meiran 1996). Meiran and Gotler (2001) found a task-shifting cost in both young adults and elderly participants. There is also a strong relationship between the time taken to complete a task and the cost of switching between tasks (Ward et al. 2001). Meiran and Gotler (2001) also studied the relationship between objective time and switching cost in different age groups. The largest effect they found was in the duration of the response selection in older adults, especially on the duration of processing stages preceding or following response selection. These findings indicate that time is associated with switching cost. However, to our knowledge, no researchers have tested the relationship between switching cost and duration judgment.

The prediction is that prospective reproduction of an interval should be shorter if more task switching was required than if the same tasks were performed but less task switching was required. The reason for this prediction is that as more attentional resources are allocated to control switching, fewer attentional resources remain to perform timing.

Retrospective reproduction of an interval during which more task switching is required should be longer than that of an interval during which less switching is required. The reason for this prediction is that more frequent switching from one task to another entails more contextual changes than if less frequent switching is required. Task switching may also produce greater segmentation of memory structures.

Zakay and Block (unpublished results) designed an experiment to test these hypotheses. The experiment is a conceptual replication of Block's (1992) Experiments 1 and 2 in a single experiment, so that it is possible to investigate interactions between processing difficulty and the high-level processes assumed to be involved in the control of task switching. The materials and methods were similar to those used by Zakay (Zakay 1989 (Experiments 1 and 3), Zakay 1993b, Zakay and Fallach 1984). Task difficulty (easy vs. difficult) and task switching (low vs. high) were both manipulated.

A total of 96 undergraduate students were tested individually. Each student was asked to perform two variants of the Stroop (1935) task. Participants who performed difficult tasks performed two tasks: the color-word (CW) task, in which a color word appears in an incongruent color (e.g., the green-colored word "red"), and the participant names the color in which the word appears; and the word-color (WC) task, which involves the same stimuli as the CW task, but the participant names the word. Participants who performed easy tasks performed two tasks: the word (W) task, in which a common word appears in white on a black background and the participant names the word; and the color (C) task, in which the person names the color of a colored square. Participants were told that the tasks could appear in any order, and that the word "color" or word would be presented with each stimulus to inform them what they should name for that item. They were told that the series of stimuli would begin with the word "start" and would end with the word "stop". Participants in the prospective condition were also told that following the presentation of the stimuli, they would be asked to estimate the interval between the "start" and "stop" cues.

The words "start" and "stop" were presented for 1 s each. The interval between these signals was 12 s, and during this interval, six stimuli were presented. At the start of each 2-s period, the cue "color" or "word" was presented, followed shortly thereafter by the presentation of the stimulus. Both terminated simultaneously at the end of the 2-s period. Participants in the high task-switching condition had three changes in processing task during the time period. Those in the difficult-task, high-switching combination of conditions performed the tasks in the order: CW, WC, WC, CW, CW, WC. Those in the easy-task, high-switching combination performed the tasks in the order: C, W, W, C, C, W. Participants in the low-switching condition had only one change in processing task during the time period. Those in the difficult-task, low-switching combination of conditions performed the tasks in the order: CW, CW, CW, WC, WC, WC. Those in the easy-task, low-switching combination performed the tasks in the order: C, C, C, W, W, W.

Following the 12-s time period, participants in both the prospective and the retrospective conditions were asked to reproduce the time period by pressing a button for the same length of time that had elapsed between the "start" and "stop" signals.

The mean reproduction in each combination of conditions is shown in Table II. There was a significant three-way interaction of duration-judgment paradigm, task difficulty, and task switching. In the prospective paradigm, reproductions were significantly longer for an easy task or a low-switching task, as compared to a difficult task or a high-switching task. In the retrospective paradigm, the opposite pattern of results was found: reproductions were significantly longer for a difficult

Table II

Task-switching experiment

	Duration-Judgment Paradigm			
	Prospective		Retrospective	
Task Switching	Task Difficulty			
	Easy	Difficult	Easy	Difficult
Low	8.81	6.81	5.07	6.41
High	6.54	5.91	8.02	9.55
Mean	7.67	6.36	6.54	7.98

Mean reproduced duration (in seconds) in each condition.

task or a high-switching task, as compared to an easy task or a low-switching task. The findings of this experiment reveal substantial differences between reproductions in the two paradigms. The findings in the prospective paradigm support an attentional model, whereas the findings in the retrospective paradigm support a contextual-change model. The prospective reproduction data also provide new evidence that task switching demands attentional resources, because prospective reproductions shortened if there had been more task switching. Prospective reproductions in the high-switching condition were shorter than they were in the low-switching condition for both the easy and the difficult tasks. This supports empirical evidence, cited earlier, about a unique switching cost that is different than that caused by task difficulty. The finding that retrospective reproductions lengthened if there was greater task switching, added to the increase caused by task difficulty, supports the notion that each manipulation produces contextual changes that are encoded in memory.

The evidence from both experiments we reviewed here reveals a double dissociation between prospective and retrospective duration judgments of short intervals during which a person either performed or did not perform high-level, executive-control processes. This evidence further supports the notion of a dissociation between experienced and remembered duration. If a person is told that timing is relevant (the prospective paradigm) but the information-processing situation calls for high attentional demands, he or she may not be able to attend much to time, and prospective judgments may become similar to retrospective judgments (cf. Brown 1985). Another situation that may change a timing process from a prospective one to a retrospective one occurs if the duration judgment is delayed after the termination of the target interval (Zakay and Fallach 1984). However, in both conditions there is a shift from one timing process to the other, and this does not necessarily imply that the processes are similar. Thus, existing evidence requires a distinction between retrospective and prospective duration judgment processes.

BRAIN RESEARCH

Research is needed to clarify the brain areas that are involved in prospective and retrospective timing. It appears that widely distributed brain structures are involved in various aspects of psychological time. Among these brain structures are the cerebellum, the lateral inferior parietal cortex, the premotor cortex, and the dorsolateral prefrontal cortex (Diedrichsen et al. 2003, Fuster 2000, Rao et al. 2001, Walsh 2003). Much less is known about exactly how time-related information is neurally implemented in these areas, as well as how these areas intercommunicate.

In the retrospective paradigm, remembered duration lengthens proportionally to the number of changes in cognitive context that were encoded during the time period and are able to be retrieved after it ends. In this paradigm (as well as in the prospective paradigm if there are high information-processing demands), duration judgments are based primarily on the encoding and retrieval of information from an extensive neuronal network that subserves episodic remembering. In order to judge a duration, a person must distinguish events that occurred during the target time period from events that occurred outside of the time period. People do this by retrieving contextual information, much of which is automatically encoded along with nontemporal information (Block and Zakay 2001, Hintzman et al. 1973). Two major brain structures are implicated. Evidence suggests that the dorsolateral prefrontal cortex may generate, in a rather automatic way, changing contextual information (Block 1996, Fuster 2000). This information is apparently transmitted by means of direct subcortical connections to the hippocampus, where it is neurally associated with nontemporal information and stored in various areas of the cortex that were specifically involved in processing that nontemporal information. Subsequently, when a person is asked to judge a duration in retrospect, the contextual information is retrieved along with the memories of events that occurred during the target duration. Evidence from brain-imaging studies suggests that the left-hemisphere prefrontal cortex largely subserves the encoding of information in the episodic-memory system and that the right-hemisphere prefrontal cortex largely subserves the retrieval of the previously encoded information (Tulving et al. 1994).

In the prospective paradigm, experienced duration lengthens proportionally to the amount of attention that a person allocates to processing temporal information (attention to time). Thus, prospective timing is ordinarily a dual-task situation in which a person must allocate resources from a common pool of limited attentional resources (Kahneman 1973, Zakay and Block 1997). Several widely distributed areas of the brain are implicated in phenomena involving attention, including the thalamus, the parietal lobes, and the anterior cingulate cortex (Posner and Raichle 1994). In humans, the attentional allocation policy is largely under conscious control. The likely candidate for a structure that subserves the allocation of attention to external events or to time is the anterior cingulate cortex. This brain area is located in the anterior part of the longitudinal fissure dividing the two cerebral hemispheres. The precise neural consequences of a person's decision to attend to time are unclear. One possibility is that when a person decides to attend to time (and is able to do so, given the current information-processing demands), contextual information associated with the previous act of attending to time, including its approximate recency, is retrieved (Block 2003). This increase in accumulated age information may give rise to the lengthening of experienced duration that is revealed in judgments of duration in the prospective paradigm.

In short, several widely distributed but closely interconnected brain structures apparently subserve retrospective and prospective duration timing. However, additional research on duration timing is clearly needed to clarify the neural interrelationships between the anterior cingulate cortex, the dorsolateral prefrontal cortex, and the hippocampus, along with the possible roles of other brain structures.

ACKNOWLEDGEMENTS

This research was supported by the Israel-Academy of Sciences grant to Dan Zakay. The order of authorship was determined randomly.

REFERENCES

Baddeley AD, Hitch GJ (1994) Developments in the concept of working memory. Neuropsychology 8: 485-493.

Block RA (1974) Memory and the experience of duration in retrospect. Mem Cognit 2: 153-160.

Block RA (1978) Remembered duration: effects of event and sequence complexity. Mem Cognit 6: 320-326.

Block RA (1989) Experiencing and remembering time: affordances, context and cognition. In: Time and human cognition: a life-span perspective (Eds. I. Levin and D. Zakay). North-Holland, Amsterdam, p. 333-363.

Block RA (1990) Models of psychological time. In: Cognitive models of psychological time (Ed. R.A. Block). Erlbaum, Hillsdale, p. 1-35.

Block RA (1992) Prospective and retrospective duration judgment: the role of information processing and memory. In: Time, action and cognition: towards bridging the gap

(Eds. F. Macar, V. Pouthas and W.J. Friedman). Kluwer Academic, Dordrecht, p. 141-152.
Block RA (1996) Psychological time and memory systems of the brain. In: Dimensions of time and life (Eds. J.T. Fraser and M.P. Soulsby). International Universities Press, Madison, p. 61-76.
Block RA (2003) Psychological timing without a timer: the roles of attention and memory. In: Time and mind II: Information-processing perspectives (Ed. H. Helfrich). Hogrefe & Huber, Seattle, p.41-59.
Block RA, Reed MA (1978) Remembered duration: Evidence for a contextual-change hypothesis. J Exp Psychol (Hum Learn) 4: 656-665.
Block RA, Zakay D (1996) Models of psychological time revisited. In: Time and mind (Ed. H. Helfrich). Hogrefe & Huber, Kirkland, p. 171-195.
Block RA, Zakay D (1997) Prospective and retrospective duration judgments: a meta-analytic review. Psychon Bull Rev 4: 184-197.
Block RA, Zakay D (2001) Retrospective and prospective timing: memory, attention, and consciousness. In: Time and memory. Issues in philosophy and psychology (Eds. C. Hoerl and T. McCormack). Clarendon Press, Oxford, p. 59-76.
Block RA, Zakay D, Cloninger MA (2000) Face and time: evidence for encoding interference. Abstracts of the Psychonomic Society Meeting 5: 100.
Block RA, Zakay D, Richmond AS (2003) Automatic and intentional processes in face encoding. Abstracts of the Psychonomic Society Meeting 8: 65.
Brown SW (1985) Time perception and attention: the effects of prospective versus retrospective paradigms and task demands on perceived duration. Percept Psychophys 38: 115-124.
Brown SW (1997) Attentional resources in timing: interference effects in concurrent temporal and nontemporal working memory tasks. Percept Psychophys 59: 1118-1140.
Brown SW, Stubbs DA (1992) Attention and interference in prospective and retrospective timing. Perception 21: 545-557.
Craik FIM, Tulving E (1975) Depth of processing and retention of words in episodic memory. J Exp Psychol 104: 268-294.
Diedrichsen J, Ivry RB, Pressing J (2003) Cerebellar and basal ganglia contributions to interval timing. In: Functional and neural mechanisms of interval timing (Ed. W.H. Meck). CRC Press, Boca Raton, p. 457-483.
Fraisse P (1963) The psychology of time (Trans. J. Leith). Harper & Row, New York, p. 199-250.
Fuster JM (2000) Prefrontal neurons in networks of executive memory. Brain Res Bull 52: 331-336.
Gopher D (1993) The skill of attention control: acquisition and execution of attention strategies. In: Attention and performance XIV (Eds. D.E. Meyer and S. Kornblum). MIT Press, Cambridge, p. 299-322.
Gopher D (1996) Attention control: explorations of the work of an executive controller. Brain Res Cogn Brain Res 5: 23-38.
Gopher D, Armony L, Greenshpan Y (2000) Switching tasks and attention policies. J Exp Psychol Gen 129: 308-339.
Hicks RE, Miller GW, Kinsbourne M (1976) Prospective and retrospective judgments of time as a function of amount of information processed. Am J Psychol 89: 719-730.
Hintzman DL, Block RA, Summers JJ (1973) Contextual associations and memory for serial position. J Exp Psychol 97: 220-229.
Just MA, Carpenter PA (1987) The psychology of reading and language comprehension. Allyn & Bacon, Boston, 460 p.
Kahneman D (1973) Attention and effort. Prentice-Hall, Englewood Cliffs, 246 p.
Macar F (1996) Temporal judgments on intervals containing stimuli of varying quantity, complexity and periodicity. Acta Psychol (Amst) 92: 297-308.
Macar F, Grondin S, Casini L (1994) Controlled attention sharing influences time estimation. Mem Cognit 22: 673-686.
Meiran N (1996) Reconfiguration of processing made prior to task performance. J Exp Psychol Learn Mem Cogn 22: 1423-1442.
Meiran N, Gotler A (2001) Modelling cognitive control in task switching and ageing. Eur J Cogn Psychol 13: 165-186.
Meyer DE, Kieras ED (1997) A computational theory of executive cognitive processes and multiple-task performance: I. Basic mechanisms. Psychol Rev 104: 3-65.
Mistler-Lachman JL (1975) Queer sentences, ambiguity, and levels of processing. Mem Cognit 3: 395-400.
Ornstein RE (1969) On the experience of time. Penguin, Harmondsworth, 126 p.
Posner MI, Peterson SE (1990) The attention system of the human brain. Annu Rev Neurosci 13: 25-42.
Posner MI, Raichle ME (1994) Images of mind. Freeman, San Francisco, p. 153-179.
Posner MI, Peterson SE, Fox PT, Raichle ME (1988) Localization of cognitive operations in the human brain. Science 240: 1631-1637.
Pouthas V, Perbal S (2004) Time perception does not only depend on accurate clock mechanisms but also on unimpaired attention and memory processes. Acta Neurobiol Exp (Wars) 64: 367-385.
Poynter WD (1983) Duration judgment and the segmentation of experience. Mem Cognit 11: 77-82.
Rao SM, Mayer AR, Harrington DL (2001) The evolution of brain activation during temporal processing. Nature Neurosci 4: 317-323.
Shallice T (1994) Multiple levels of control processes. In: Attention and performance 15: Conscious and nonconscious information processing (Eds. C. Umilta and M. Moscovitch). MIT Press, Cambridge, p. 395-420.

Stine-Marrow EAL, Loveless MK, Soldenberg LM (1996) Resource allocation in on-line reading by younger an older adults. Psychol Aging 11: 475-486.

Stroop JR (1935) Studies of interference in serial verbal reactions. J Exp Psychol 18: 643-662.

Tulving E, Kapur S, Craik FI, Moscovitch M, Houle S (1994) Hemispheric encoding/retrieval asymmetry in episodic memory: positron emission tomography findings. Proc Natl Acad Sci U S A 91: 2016-2020.

Walsh V (2003) Time: the back-door of perception. Trends Cogn Sci 7: 335-338.

Ward G, Roberts MJ, Phillips LH (2001) Task-switching costs, Stroop-costs, and executive control: a correlational study. Q J Exp Psychol 54A: 491-512.

Wearden J (2004) Decision processes in models of timing. Acta Neurobiol Exp (Wars) 64: 303-317.

Zakay D (1989) Subjective time and attentional resource allocation: an integrated model of time estimation. In: Time and human cognition: a life-span perspective (Eds. I. Levin and D. Zakay). North-Holland, Amsterdam, p. 365-397.

Zakay D (1993a) Relative and absolute duration judgments under prospective and retrospective paradigms. Percept Psychophys 54: 656-664.

Zakay D (1993b) Time estimation methods – do they influence prospective duration estimates? Perception 22: 91-101.

Zakay D (1998) Attention allocation policy influences prospective timing. Psychon Bull Rev 5: 114-118.

Zakay D, Block RA (1996) The role of attention in time estimation processes. In: Time, internal clocks and movement (Eds. M.A. Pastor and J. Artieda). Elsevier Science, Amsterdam, p. 143-164.

Zakay D, Block RA (1997) Temporal cognition. Curr Dir Psychol Sci 6: 12-16.

Zakay D, Fallach E (1984) Immediate and remote time estimation – a comparison. Acta Psychol (Amst) 57: 69-81.

Zakay D, Shub J (1998) Concurrent duration production as a workload measure. Ergonomics 41: 1115-1128.

Zakay D, Tsal Y, Moses M, Shahar I (1994) The role of segmentation in prospective and retrospective time estimation processes. Mem Cognit 22: 344-351.

Zakay D, Block RA, Tsal Y (1999) Prospective duration estimation and performance. In: Attention and performance XVII. Cognitive regulation of performance: interaction of theory and application (Eds. D. Gopher and A. Koriat). MIT Press, Cambridge, p. 557-580.

Received 11 December 2003, accepted 26 January 2004