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Time perception depends on accurate clock mechanisms as well as unimpaired attention and memory processes

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Abstract. We report a series of studies aimed at characterizing the relationships between duration judgments and slowing down of the internal clock, attention and memory deficits. Different groups of participants (elderly people, patients with Parkinson's disease, patients with severe traumatic brain injury, and patients with temporal lobe lesions) performed a duration reproduction task and a duration production task in two conditions: a control counting condition and a concurrent reading condition. Participants were also administered reaction time tasks, tapping tasks, and a battery of attention and memory tests. The results allow us to characterize the relationships between cognitive deficits and impaired duration reproductions and productions in each group. Moreover, results as a whole clarify the respective weight of processing speed, attention and memory in both tasks, and allow better insight into the theoretical models of psychological time.

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Key words: aged people, brain damaged patients, clock speed, attention, memory, duration reproduction, duration production

INTRODUCTION

Although time is essential information for daily life, the way in which we code temporal information is as yet little understood. Indeed there is no sensory modality by which time can be directly perceived. Gibson (1975) entitled a chapter "events are perceivable, but time is not" and Michon (1990) wrote "time is a derived entity in the conscious experience". Since the early sixties, however, models of temporal cognition have attempted to account for behavioral data showing that humans and animals are sensitive to time and are able to process this dimension of their environment. Most psychological models assume that temporal judgments are based on three processing stages. According to the model which has been prominent these last twenty years (Church 1984), the first component consists of an oscillatory pacemaker emitting pulses at a mean constant rate. These pulses are gated into an accumulator when a switch is closed, i.e. when the signal duration is being processed. The content of the accumulator provides the raw material for measuring time (clock stage). The outcome from the accumulator corresponding to the current time is transiently stored in a working memory system for comparison with the content of reference memory, which contains a long-term memory representation of the approximate number of pulses accumulated on past trials (memory stage). Finally, a mechanism compares the current duration values with those in working or reference memory to decide on the adequate temporal response (decision stage) (Fig.1).

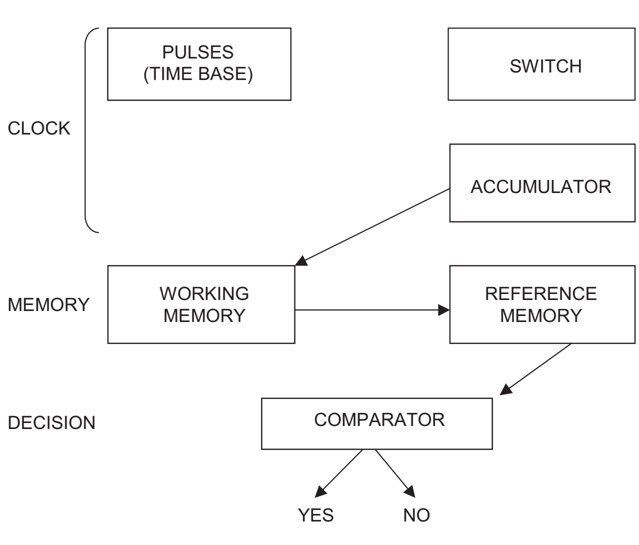

Fig. 1. Model of temporal information processing (redrawn from Church 1984).

In addition, attentional factors have been shown to play an important role in time perception. Thus, when less attention is allocated to time, which is the case in studies using dual-task paradigms, reduction in subjective duration has been observed. These shorter experienced durations are compatible with Church's model. They may result from the fact that fewer pulses have been accumulated in the counter or have been lost during the memory storage. The more attention is given to non-temporal processing, the more temporal pulses would be lost and hence the more subjective duration would shorten (Zakay 1989, Zakay and Block 2004).

GENERAL METHODOLOGY

The aim of the studies reported below was to characterize the relationships between duration judgments and disruption in the clock and memory stages as well as attention deficits. We assumed that aging and lesions would differentially affect clock, memory and decision processes. Several studies (e.g., Malapani et al. 1998, Nichelli et al. 1995, Pastor et al. 1992) have already been conducted with patients, but the originality of our approach was to use the same comprehensive design for investigating temporal judgments of older adults and of patients with various cerebral lesions. We conducted a series of studies as follows: (i) in older adults, who have been shown to process information more slowly, to have reduced attentional capacities and to suffer from memory deficits (Perbal et al. 2002); (ii) in patients with Parkinson's disease, whose dopaminergic depletion has been assumed to lead to changes at the clock stage and/or at the memory stage (Perbal S, Deweer B, Pillon B, Vidaihet M, Dubois B, Pouthas V, in press); (iii) in patients with severe traumatic brain injury, who exhibit attention and memory deficits (Perbal et al. 2003); (iv) in patients with medial-temporal lobe lesions, who suffer from long-term memory deficits (Perbal et al. 2000, 2001).

Tasks

In each of these studies, we used two temporal tasks, i.e. reproduction and production of duration, assuming that clock, attention, memory and decision processes would be differentially involved in these tasks. In the duration reproduction task the participants had to evaluate the display duration of a blue square presented in the center of a computer screen. At the beginning of each trial, the sentence "Evaluate the target duration" appeared at the bottom of the computer screen and was simultaneously pronounced aloud by the experimenter. Then, the duration was presented (encoding). After the encoding phase, the sentence "Reproduce the duration just evaluated" was displayed and read by the experimenter. Then, the blue square reappeared and the participants had to press the response panel to erase it when they judged that the previously displayed duration was over (reproduction phase). This task not only requires short-term memory storage during the encoding of the target duration, but might also necessitate retrieval from long-term storage, because of the limited capacity of short-term memory. In the duration production task the participants had to cause the stimulus (blue square) to remain displayed in the center of the computer screen for the target duration given in seconds. At the beginning of each trial, for example the sentence "Produce 14 seconds" was written at the bottom of the screen and simultaneously pronounced aloud by the experimenter. Then, the blue square appeared and the subjects had to press on the response panel when they judged that the given duration had elapsed. Performance in this task could depend on the speed at which pulses are accumulated, in other words on clock speed and information processing speed. In addition, this task not only requires short-term (working) memory storage in order to maintain the temporal information (i.e., time basis pulses) throughout the trial, but might also necessitate long-term memory in which the representation of several durations would be stored. Because the durations to produce are given in conventional units of time (seconds), this long-term memory could be viewed as semantic memory.

The three target durations were 5 seconds (considered as relatively short), 14 seconds (medium) and 38 seconds (long). We assumed that encoding temporal information (number of pulses) for reproducing the 38 seconds duration and perhaps the 14 seconds duration would exceed the short-term memory capacity and would require to be transferred (even transiently) in a long-term memory store. Furthermore, the involvement of the different processes subtending time perception could depend on the conditions in which the tasks are performed. In our series of studies subjects performed the time-reproduction task and the time production task in two conditions, a control counting condition and a concurrent reading condition. In the control counting condition, the participants were told to count aloud for the stimulus duration as regularly as possible and at the rate they preferred throughout the encoding and the reproduction phases of the reproduction task on one hand and, during the production of the stimulus duration, given in seconds, in the production task on the other hand. In the concurrent reading condition, digits were presented in random order in the center of the blue square, with a random inter-digit interval between 350 and 950 ms. Subjects were told to read aloud these digits throughout the encoding phase of the reproduction task and until they felt that the target duration was over in the production task. In the reproduction phase proper (of the reproduction task), the square without digits appeared on the screen and participants had to press the response panel after a time subjectively equal to the one evaluated during the encoding phase. Using these two conditions we intended to study the effect of amount of attention dedicated to the evaluation of duration. The reproduction and production tasks in the concurrent condition require simultaneously evaluating the target duration and performing the concurrent reading task. In this condition, attention is divided between the two types of information processing. Less attention allocated to the temporal task causes a loss of pulses. This leads to opposite effects in the two temporal tasks. On the one hand, a smaller number of pulses accumulated during the encoding of a duration results in a shorter reproduction of duration than the real time. On the other hand, in the production task a loss of pulses during the current duration requires accumulating a greater number of pulses before the target duration (given in conventional units of time) is judged over, thus leading to longer productions. We assumed that these effects would be stronger in patients with reduced attentional resources.

Different neuropsychological tests were used to assess memory. The forward and backward digit span tests from the Weschler memory scale (Wechsler 1981) as well as the forward and backward spatial span tests from Corsi's block-tapping test (Milner 1971) (without a concurrent task) were used to evaluate short-term memory, the Corkin working memory test (Corkin 1965) (concurrent task) to evaluate working memory and the Grober and Buschke test (Grober and Buschke 1987) to evaluate episodic memory. Information processing speed was assessed by a simple reaction-time task, in which participants were required to press on the response panel with the right hand as fast as possible in response to a stimulus (a blue square) that appeared in the center of the computer screen, at a short random inter-stimulus onset interval (ranging from 1 000 to 2 000 ms) or at a long random interval (from 2 000 to 3 000 ms).

Data Analysis

Two indices of performances were computed to assess accuracy and precision. The first was computed by taking the ratio of the duration reproduced or produced to the target duration (5, 14, or 38 s). This index reflects the accuracy of temporal judgments. Statistical analyses were carried out on this ratio because it allowed for comparisons of different target duration estimations. The other performance index was the coefficient of variation (CV), computed by taking the ratio of the standard deviation to the reproduction or production mean. This index represents the variability of temporal judgments of each participant and allows one to evaluate how consistent subjects are in their reproductions or productions of the same target duration. As the first index, it allowed for comparisons of variability for different target durations.

To summarize, in each study we obtained accuracy and variability indices in the duration reproduction and the duration production tasks, as well as memory scores and reactions times. In order to test relationships between duration judgments and memory scores, as well as between duration judgments and processing speed, Pearson correlations were calculated between temporal accuracy index in the two temporal tasks (i.e., reproduction and production) and memory scores and reactions times, and also between temporal variability index in the two temporal tasks (i.e., reproduction and production) and memory scores and reactions times. Then, a series of regression analyses were conducted in order to determine whether the differences observed in memory and processing speed in aged people compared to young adults, as well as the differences observed in brain damaged patients compared to healthy participants, mediate the differences obtained between groups in time estimation accuracy or variability. Finally, we compared the observed relationships in the different studies.

Therefore, we first describe the specific aims, main results and conclusions of each study and then discuss the total pattern of results.

STUDY ON OLDER ADULTS

Intoduction

This study was aimed at investigating the relationships between changes in time estimation and changes in processing speed, attention and memory with aging. Some authors have concluded that the aged-related differences in duration judgments are due to slowing down of the internal clock with aging (Craik and Hay 1999, Fraisse1957, Surwillo 1968). The assumption of a slowing of an internal timing mechanism has also been proposed (Schroots and Birren 1990, Surwillo 1968) to account for the slower information processing found in older adults on perceptual and motor tasks (Cerella 1990, Salthouse 1994, 1996, Wearden et al. 1997). Others authors have suggested that changes in time estimation with aging are associated with reduced attentional resources or memory deficits in older adults (Block et al. 1998, Lustig and Meck 2001, Vanneste and Pouthas 1999, Wearden et al. 1997). The comprehensive design described above provided us with the means to determine the respective weights of clock slowing, reduced attentional capacities and memory deficits on age-related differences in duration judgments.

Methods

Two groups of volunteers participated in this study: 22 young adults (12 women) with a mean age of 23.8 years and with an average of 12 years of education; 24 older adults (15 women) with a mean age of 68.6 years and with an average of 8 years of education. No participant had a history of neurological or psychiatric disorders.

Results

TIME REPRODUCTION AND TIME PRODUCTION TASKS

ANOVAs with a between-subject factor (group: younger and older adults) and a within-subject factor (duration: 5, 14, and 38 s) carried out on the time estimation accuracy index showed that both younger and older adults accurately reproduced and produced the three target durations in the counting condition. By contrast, both age groups made shorter reproductions and longer productions than the three target durations in the concurrent reading condition. In addition, these effects were magnified with age. Duration reproductions were significantly shorter ($F_{1, 44}$= 23.93, P<0.001) and duration productions were significantly longer ($F_{1, 44}$=26.4, P<0.001) in the older adults than in the younger ones (Fig. 2). ANOVAs carried out with the design described above on the time estimation variability index (i.e., the coefficient of variation) did not yield any significant effect of group.

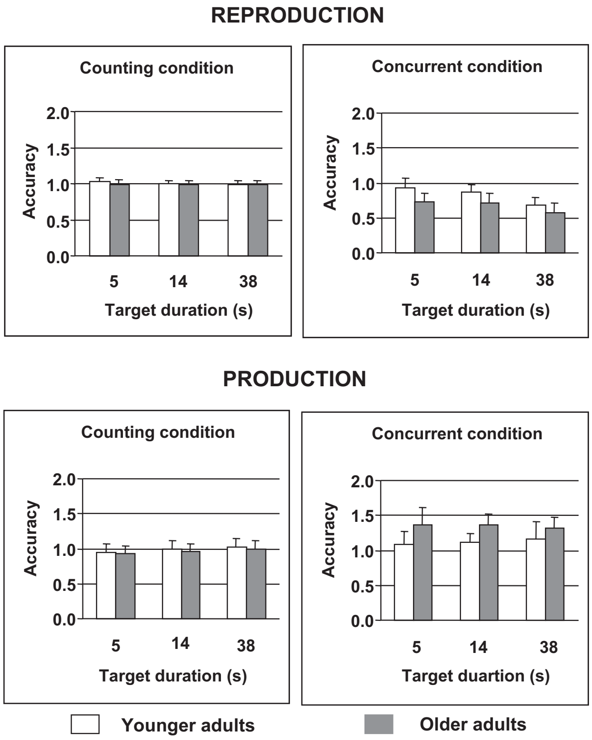

Fig. 2. Temporal accuracy (estimated duration/target duration) on the reproduction and production tasks, for the three target durations (5, 14, and 38 seconds) and the two conditions (control counting condition and concurrent reading condition) in young and old participants.

SIMPLE REACTION TASK

An ANOVA revealed a significant main effect of group, $F_{1,42}$=32.4, P<0.001, indicating that the older adults were significantly slower than the younger ones (mean reaction time = 325 ms vs. 251 ms).

NEUROPSYCHOLOGICAL MEMORY TESTS

The analyses (using Mann-Whitney comparisons) revealed that memory was significantly poorer in the older than in the younger adults on verbal short-term memory, working memory, and episodic memory tests (Table I).

RELATIONSHIPS BETWEEN THE REPRODUCTION AND PRODUCTION TASKS, REACTION TIME TASK AND NEUROPSYCHOLOGICAL MEMORY TESTS

Overall correlations were calculated between the accuracy index obtained in the concurrent reading condition of the reproduction task and both the processing speed and memory scores: time estimation accuracy was significantly correlated with short-term memory, working memory and episodic memory and simple reaction times. Correlations were also calculated for the concurrent reading condition of the production task: time estimation accuracy was correlated with simple reaction times and with working and episodic memory scores. Multiple regression analyses revealed that working memory limitations account for the age-related variance in reproduction accuracy and that processing speed was the best predictor of the age-related variance in production accuracy.

Table I

Comparison between memory scores and reaction times of the young and old participants

	Younger	Older	
Memory			
Short-term memory	6.08	5.5	P<0.01
Working memory	4.7	3.3	P<0.001
Episodic memory	28.6	25	P<0.001
Processing speed			
Reaction time	281 ms	325.5 ms	P<0.001

Discussion and Conclusions

The results showed age-related differences in time estimation accuracy when time estimation was performed in the concurrent reading condition: i.e., shorter reproductions and longer productions than the real time in both age groups, but these effects were stronger in older adults. This is consistent with literature (for review see Brown 1997) showing that time units are lost in case of attention sharing between temporal information processing and non temporal information processing (i.e., dual-task paradigms), which lead to shorter reproductions and longer productions. Attentional resources being reduced with aging, the effect was stronger in older adults. Importantly, results show that changes in time estimation with aging are related to different cognitive deficits depending on the conditions in which temporal judgments are collected. Shorter reproductions in older adults are better explained by working memory limitations, whereas longer productions in older adults are better explained by slower processing speed.

STUDY ON PATIENTS WITH PARKINSON'S DISEASE (PD)

Introduction

Dopamine (DA) depletion in PD patients leads to both time estimation and motor timing deficits. Usually following administration of levodopa (L-Dopa) a significant improvement of temporal performance is observed (Harrington and Haaland 1999, Lange et al. 1995a, Malapani et al. 1998, 2002, Pastor et al. 1992). According to the authors inaccurate and variable duration judgments in PD patients may be due to changes occurring either at the clock stage of temporal processing (i.e., slowing down of an internal timekeeping) or at its memory stage (working memory impairment). The possible influence of deficits in attentional processes on temporal accuracy in PD patients has also been considered by several authors. As DA depletion might affect the rate of internal timekeeping as well as memory functions, both should be taken into account when investigating temporal processing in the seconds-to-minute range in PD patients. Collecting performance on the two tasks (duration production and reproduction) was aimed at disentangling the effects of impaired memory and changes in the rate of the internal clock. Indeed, the reproduction task should provide information about the memory component and the comparison of durations in memory whereas the production task would reveal effects of changes in the speed of the internal clock. Moreover, the dual-task paradigm (i.e., concurrent reading condition) would reveal the possible contribution of defective attention in the patients.

Methods

The patient group with idiopathic Parkinson's disease (PD) included 7 women and 11 men, with a mean age of 59 years (range = 48-77, SD = 8) and a mean education level of 10.9 years (range = 6-17, SD = 3.6). All PD patients were receiving dopaminergic replacement therapy and were tested during their normal medication cycle (i.e., "on state"). Disease severity was assessed by a board-certified neurologist using the unified Parkinson's disease rating scale (UPDRS) (Fahn et al. 1997), and the Hoehn-Yahr scale (H&Y) (Hoehn and Yahr 1967). UPDRS was performed when patients were on medication (mean UPDRS-on = 11.7, range = 1-25, SD = 2.9) and off medication (UPDRS-off = 28.4, range = 11-71, SD = 17). The mean Hoehn-Yahr stage when patients were off medication was 2.2 (range = 1-4, SD = 1), and the mean disease duration was 8.9 years (range = 2-20, SD = 5.9). The control group included 10 women and 8 men, with a mean age of 60.3 years old (range = 50-77, SD = 8.8) and a mean education level of 9.2 years (range = 7-17, SD = 3). None of the PD patients and control participants reached the dementia criteria evaluated by the Mattis dementia rating scale (Mattis 1988), for which no significant difference between the two groups was found ($Z = 1.02$, $P>0.10$).

Results

TIME REPRODUCTION AND TIME PRODUCTION TASKS

An ANOVA with a between-subject factor (group: patients and controls) and two within-subject factors (duration and condition) was carried out on the accuracy index observed in the reproduction task. It showed no main effect of group ($F_{1,34}<1$), and no significant interaction with the group variable. Reproductions of patients did not differ from those of controls whatever the duration or the condition. In the control counting condition, the three target durations were accurately reproduced by patients and controls (as indicated by the ratio equal to 1). In the concurrent reading condition the three target durations were under-reproduced by both groups (Fig. 3). An analysis of variance carried out on the accuracy index obtained in the production task showed a main effect of group ($F_{1,34}=14.5$, $P<0.001$). Furthermore, the analysis revealed a significant group × duration × condition interaction ($F_{2,68}=3.29$, $P<0.05$). In the control counting condition, control participants accurately produced the target durations (mean ratios ≅ 1 for 5, 14 and 38 s) whereas PD patients produced shorter durations than the requested target durations (mean ratios = 0.9), even though the difference between groups was not significant (all $P>0.20$). By contrast, in the concurrent reading condition, the productions of control participants were longer than the target durations (mean ratios = 1.3) whereas the productions of PD patients became shorter as the target duration increased (mean ratios = 1.1, 0.9, 0.8, linear component $F_{1,17}=12.4$, $P<0.01$) (Fig. 3).

The analyses of variance carried out on the variability index (CV) revealed no significant effect of group either in the reproduction task or in the production task.

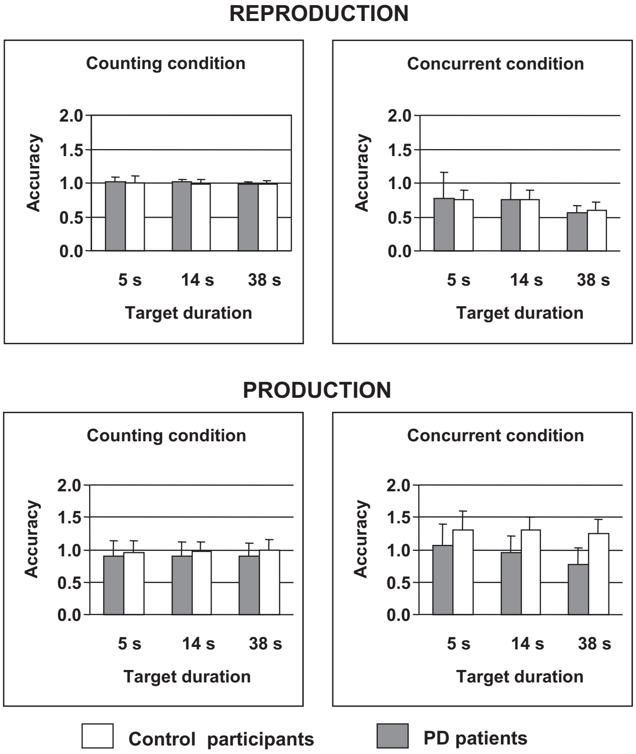

Fig. 3. Temporal accuracy (estimated duration/target duration) on the reproduction and production tasks, for the three target durations (5, 14, and 38 seconds) and the two conditions (control counting condition and concurrent reading condition) in PD patients and control participants.

NEUROPSYCHOLOGICAL MEMORY TESTS

The memory scores obtained by PD patients and by control participants are presented in Table II. Non-parametric analyses of variance revealed significant differences between the two groups on sub-tests of short-term memory and episodic memory. PD patients had lower performance on the Corkin test with the 10-s free retention intervals ($P<0.05$) and on the immediate recall of the Grober and Bushke test ($P<0.01$).

RELATIONSHIPS BETWEEN THE REPRODUCTION AND PRODUCTION TASKS AND NEUROPSYCHOLOGICAL MEMORY TESTS

Correlations calculated between the production accuracy index (of the concurrent reading condition) and memory scores showed that accuracy was significantly correlated with short-term memory. Multiple regression analyses revealed that short-term memory deficits account for the shorter productions of PD patients.

Table II

Comparison between memory scores and reaction times of PD patients and control participants

	Control participants	PD patients	
Memory			
Short-term memory	6.0	5.3	$P<0.05$
Episodic memory			
- immediate free recall	31.5	25.3	$P<0.01$
- immediate cued recall	47	43	ns
- delayed free recall	11.9	10.6	ns
- delayed cued recall	15.8	15.5	ns
Processing speed			
Reaction time	316 ms	283 ms	ns

Discussion and Conclusions

There was no difference between PD patients and control participants in the reproduction task whatever the condition. These results confirm and extend previous findings in medicated patients (Malapani et al. 1998, 2002, Pastor et al. 1992). In addition, they support the assumption that long-term memory is not affected to a greater extent in PD patients than in normal elderly controls. Another important finding was that durations produced by PD patients were significantly shorter than those produced by control participants in the concurrent reading condition. This finding is quite surprising since DA depletion in PD patients is assumed to slow down the speed of the internal clock and therefore to induce an underestimation of time (Lange et al. 1995b, Malapani et al. 1998). DA treatment could have abnormally increased the rate of the internal clock, leading to shorter duration productions in PD patients, but PD patients tended to over-produce the short duration (5 s), and exhibited marked underproductions of the long duration (38 s). Similar effects were previously reported in non-medicated PD patients trained to produce two durations (8 and 21 s) (Malapani et al. 1998, 2002). During the testing session, patients over-produced 8-s and under produced 21-s. This effect described as to the "migration effect" was explained by memory retrieval deficits. In our study the production task did not correlate with long-term memory scores but with short-term memory scores. This result suggests that the influence of durations on each other would occur between the different trials within a session rather than between the representations of duration in long-term memory. Therefore, in order to account for the full pattern of results that we observed, we propose that L-Dopa administration in PD patients may have counteracted the slower rate of the internal clock typically reported in non-medicated PD patients, without restoring all of the memory functions.

STUDY ON PATIENTS WITH SEVERE TRAUMATIC BRAIN INJURY (TBI)

Introduction

A few studies (Cooke and Kausler 1995, Vakil and Tweedy 1994, Vakil et al. 1991, 1998) have suggested that patients with traumatic brain injury (TBI) are impaired in memory for temporal order but, to our knowledge, our study was the first to investigate the extent to which time estimation was affected in TBI patients. Some studies have indicated that duration judgments are impaired in patients with frontal lesions (Casini and Ivry 1999, Nichelli et al. 1995, Shaw and Aggleton 1994) and that there is a high incidence of frontal-lobe dysfunction with TBI (Adams 1984, Azouvi 2000). Moreover, many studies have revealed attention and memory deficits in patients with TBI. Indeed, one complaint frequently reported by these patients concerns their inability to pay attention to more than one thing at a time (Ponsford and Kinsella 1992, Van Zomeren and Van den Burg 1985). Some authors have suggested that attention and working memory deficits in TBI patients are due to slowing of information processing (Brouwer et al. 1989, Gronwall 1987, Reitan 1958, Van Zomeren 1981, Vilkki 1992), which is one of the most frequent and persistent outcomes of TBI. Besides, studies using reaction time tasks in TBI patients have shown that processing speed is inversely correlated with the severity of injury. Based on the above studies, we assumed that frontal-lobe dysfunction, reduced attentional capacities as well as slower information processing, would affect accuracy and precision of duration judgments of patients with TBI. The effects of these deficits might depend on the time estimation task used to obtain the judgments (Zakay 1990, 1993).

Methods

The group of patients with traumatic brain injury (TBI) included 15 right-handed subjects (7 women). The mean age was 30.4 years (SD = 9, range = 19-53) and the mean level of education was 13.7 years (SD = 4, range = 7-20). The patients have been referred to a rehabilitation department after a severe traumatic brain injury, as defined by a score of 8 or less on the Glasgow coma scale (mean Glasgow score GCS of 6.4 (SD = 1.8, range = 3-8). The mean time of post-traumatic amnesia (PTA) was 88 days (SD = 73.3, range = 3-210). All patients had suffered a closed-head injury due to a road accident and were examined within a mean post-injury time of 11 months (SD = 9.6, range = 4-41). They were all physically and mentally able to understand and complete the tests. Patients with penetrating head injury and previous head injury were excluded from the study. All patients performed tests usually considered as being sensitive to the functioning of frontal lobes: the modified Wisconsin card sorting test (Nelson 1976), and the trail-making test (Reitan 1958). The mean time required to discover the three criteria (shape, color and number) on two trials was 38 seconds (range = 36-40, SD = 1.8), and the mean time of performance on the TMT was 44.3 seconds for version A (range = 24-75, SD = 13) and 71.5 seconds for version B (range = 41-98, SD = 18). Five patients showed focal prefrontal lesions on CT and/or MRI scans. However, these patients' performance did not significantly differ from patients without apparent prefrontal damage. The control group included 15 right-handed subjects (7 men) who had never suffered from a traumatic brain injury. Control subjects were individually matched to the patient group on the basis of age and education level. The mean age of the control group was 30.4 years (SD = 9, range = 20-51) and the mean level of education was 13.2 years (SD = 4.2, range = 7-20). None of TBI or control subjects had any neuropsychiatric disorders or a history of drug or alcohol abuse.

Results

TIME REPRODUCTION AND TIME PRODUCTION TASKS

Patients' reproductions and productions were not less accurate than those of controls, whatever the duration or condition ($F_{1,28}<1$, ns). In the control counting condition, the three target durations were accurately reproduced by patients and controls. In the concurrent reading condition, the three target durations were underestimated by patients and controls and accuracy decreased as the target duration increased in both groups. Duration productions were significantly shorter in the control counting condition than in the concurrent reading condition in both groups ($F_{1,28}$=15.4, P<0.001).

By contrast, reproduction variability was higher for TBI subjects than for control subjects, particularly for the duration of 14 seconds. An analysis of variance revealed a main effect of group ($F_{1\text{-}28}$=8, P<0.01), and a significant interaction between group and duration ($F_{2,56}$=4, P<0.05). Production variability was also higher for TBI subjects than for control subjects ($F_{1,28}$=5.2, P<0.05) (Fig. 4).

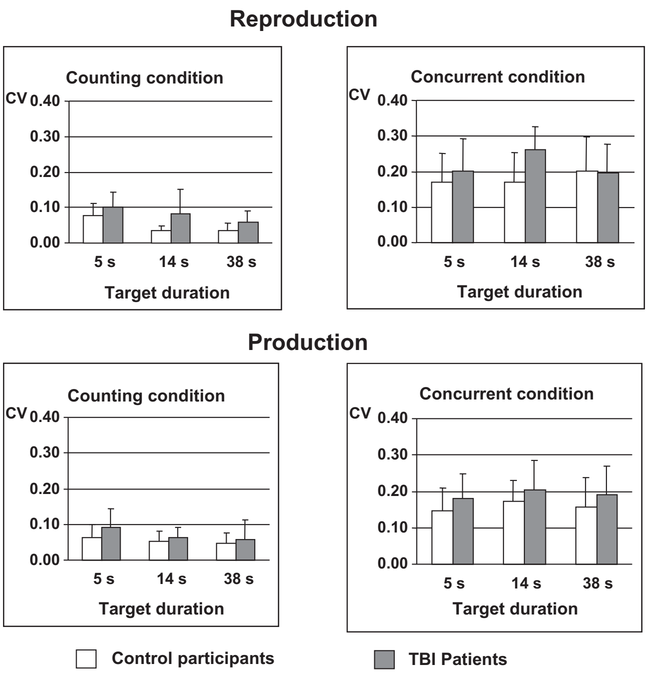

Fig. 4. Coefficient of variation (standard deviation/mean reproduction) on the reproduction and production tasks, for the three target durations (5, 14, and 38 seconds) and the two conditions (control counting condition and concurrent reading condition) in TBI patients and control participants.

NEUROPSYCHOLOGICAL MEMORY TESTS AND REACTION TIME TASK

The analyses (using Mann-Whitney comparisons) revealed that working memory and episodic memory scores were significantly poorer in TBI patients than in control participants. Moreover, the reaction time task revealed that patients were significantly slower than control participants (Table III).

RELATIONSHIPS BETWEEN THE REPRODUCTION AND PRODUCTION TASKS AND NEUROPSYCHOLOGICAL MEMORY TESTS

Analyses showed that the variability index in the reproduction task was correlated with the processing speed measure, as well as with the working memory and episodic memory scores. In the production task, the variability index was correlated only with the processing speed measure.

Table III

Comparison between memory scores and reaction times of patients with TBI and control participants

	Control participants	Patients with TBI	
Memory			
Working memory	3.3	2.9	P<0.05
Episodic memory			
- immediate free recall	30.9	35.5	P<0.05
- delayed free recall	11.2	11.8	P<0.001
Processing speed			
Reaction time	227 ms	262 ms	P<0.01

Discussion and Conclusions

Contrary to what was expected, the results showed that temporal reproduction and production performance was not less accurate in patients with TBI than in control participants in either the control counting condition or in the concurrent reading condition. However, duration judgments of patients with TBI were more variable than those of control participants. This is a very robust finding. It was indeed obtained on both tasks (duration reproduction and production) and in both conditions (control counting and concurrent reading). Only a few studies (Brouwer et al. 1989, Nichelli et al. 1995) carried out on patients with frontal lesions have reported indices of variability in duration judgments. Nevertheless when temporal variability was analyzed, it was found to be higher in frontal patients than in control participants. The results also yielded differences between the TBI patients and the control participants on processing speed measures and memory scores. TBI patients exhibited slower reaction times, and poorer working and episodic memory scores than controls. More revealing are the findings regarding the relationships between temporal variability, processing speed measures, and memory scores. In the reproduction task, the variability index was correlated with both working memory scores and processing speed measures, whereas in the production task, the variability index correlated only with the processing speed measures. In conclusion, the unexpected temporal performance pattern found in TBI patients may not reflect deficits specifically related to timing but rather to generalized attention, working memory, and processing speed problems. Based on findings reported for patients with frontal lesions, one can expect increased variability in patients with TBI regardless of whether the task requires temporal or non-temporal information processing.

STUDY ON THE AMNESIC PATIENT (AC)

Introduction

Numerous studies (Kinsbourne and Hicks 1990, Mimura et al. 2000, Richards 1973, Williams et al. 1989) concerning temporal processing in amnesic patients have shown that they can accurately evaluate short durations (less than10 seconds), whereas they consistently underestimate longer durations (more than 10 or 20 seconds). These deficits have been mainly interpreted as being due to long-term memory dysfunction. Using duration reproduction and production tasks, we investigated the timing abilities of an amnesic patient with bilateral medial temporal lesions (AC), presenting a selective deficit of episodic memory. We predicted that he would underestimate long durations in the reproduction task but, the other memory systems being preserved in this patient, we also assumed that his productions of all durations could be accurate.

Methods

The patient AC is a 40-year-old man. He was found comatose in the street in March 1987 and the coma spanned a 3-month period. A first scan showed a left subdural haematoma with extensive left hemispheric swelling. A short neuropsychological examination carried out in December 1987 revealed severe amnesia. A detailed examination was conducted in December 1988 (see Perbal et al. 2000 (Table I, p. 349)), with a follow-up memory assessment in January 1993 (see Van der Linden and Coyette 1995, Van der Linden et al. 1996). AC showed normal intellectual efficiency, he had fluent speech, and his comprehension of complex sentences was correct. There were no signs of object agnosia or apraxia, and his performances in an auditory reaction time test were normal (median reaction time = 204 ms, controls = 256 ms). His short-term (working) memory investigated by the forward digit span test and the Corsi block-tapping procedure (Milner 1971) was normal. In contrast, AC was profoundly amnesic: he was completely unable to maintain any record of ongoing events and he could not recollect episodes of his life or recount current new events. AC showed a relatively preserved ability to retrieve semantic information about people who became famous before his accident or after the onset of his amnesia. These data suggest that AC showed an impairment of episodic memory while semantic memory was relatively spared.

Forty-eight normal controls were matched to AC on the basis of educational level: 12 men and 12 women were also matched on the basis of his age (mean age = 40 years); 12 men and 12 women were young students (mean age = 23.5 years).

Results

To compare performances obtained by AC and those observed in controls, a descriptive analysis was first carried out on the mean estimation which corresponds to the target duration reproduced or produced by AC and controls. Then a statistical analysis was carried out on both the ratio DS/DO (subjective duration /objective duration) and the coefficient of variation (CV), by calculating confidence intervals with a threshold of 0.05 around the mean ratio or of controls.

As expected, the confidence intervals showed a significant difference between the reproductions of AC and those of controls for 38 s and 14 s, these durations being strongly underestimated by the patient. By contrast, the confidence intervals revealed no significant difference between the performances of AC and those of controls in the production task (Fig. 5). In other words, the performances of the amnesic patient AC showed a clear dissociation according to the task and the durations: his productions of the three durations and his reproductions of 5 s did not differ from those of the control participants (situated within the confidence intervals), whilst his reproductions of the longest duration (38 s) and even of the medium one (14 s) did not lie in the con-

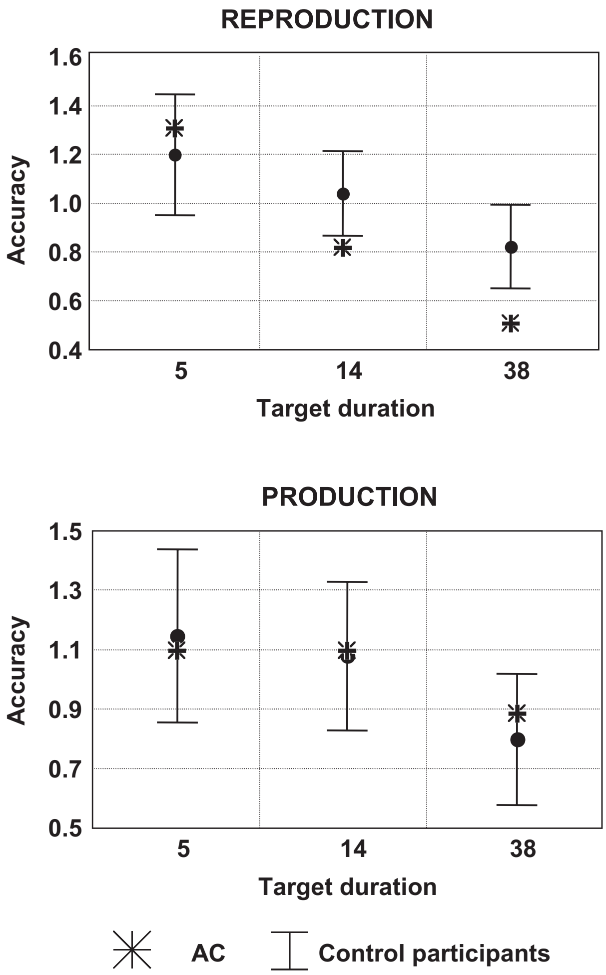

Fig. 5. Confidence intervals around the ratio of estimated duration/target duration on the reproduction and production tasks of the control participants and the mean ratio of estimated duration/target duration of the amnesic patient (AC) for the three target durations (5, 14, and 38 seconds).

fidence intervals. This dissociation was strengthened by the fact that AC's reproductions or productions were not more variable than those of controls.

Discussion and Conclusions

Considering the selectivity of AC's memory deficit due to his medial temporal lesions, the under-estimations in the reproduction task could come from a failure in the retrieval of information from episodic memory. Encoding temporal information (i.e., time basis pulses) for the medium and long durations would exceed the short-term memory capacity of AC. By contrast, productions were not impaired because representation of conventional units of time (e.g., second) stored in semantic memory would be preserved in this patient. In addition, working memory and attentional resources, which are required for accurate performance in the duration production task, were normal in the patient.

STUDY ON PATIENTS WITH RIGHT OR LEFT MEDIAL-TEMPORAL LOBE RESECTION

Introduction

The aim of this study was to gain further insight into the role of each medialtemporal lobe (MTL) in time estimation. Based on previous studies (Basso et al. 1996, Rubia et al.1997, Vidalaki et al. 1999), we predicted that patients with right MTL damage should be more impaired in time estimation than patients with left MTL damage and than normal control subjects. In the light of the episodic memory deficit due to temporal lobe dysfunction, we assumed that reproduction of long durations would be particularly disturbed, as has been observed in amnesic patients.

Methods

Eighteen patients who have undergone a right (RT) (n = 9, mean age = 33 years, range = 16-56) or left (LT) (n = 9, mean age = 35 years, range = 20-37) medial temporal lobe resection (MTL) for the relief of medically intractable epilepsy. The resection included the MTL structures (hippocampus, amygdala, parahippocampal gyrus, perirhinal cortex) as well as the temporal pole. This resection was of similar extent in both right and left hemispheres.

Eleven normal control participants served as controls (NC) (mean age = 32 years, range = 21-64). They had no history of neurological or psychiatric illness or brain injury.

Results

The analysis of variance carried out on the temporal accuracy index obtained for the three groups of participants (RT, LT, NC) in the two tasks yielded a significant interaction between group and task ($F_{2,26}$=5.41, P<0.01). Contrary to what was expected, *post-hoc* analysis showed no difference between the reproductions of the patients and those of normal controls (P>0.05). By contrast, the same *post-hoc* analysis revealed that RT

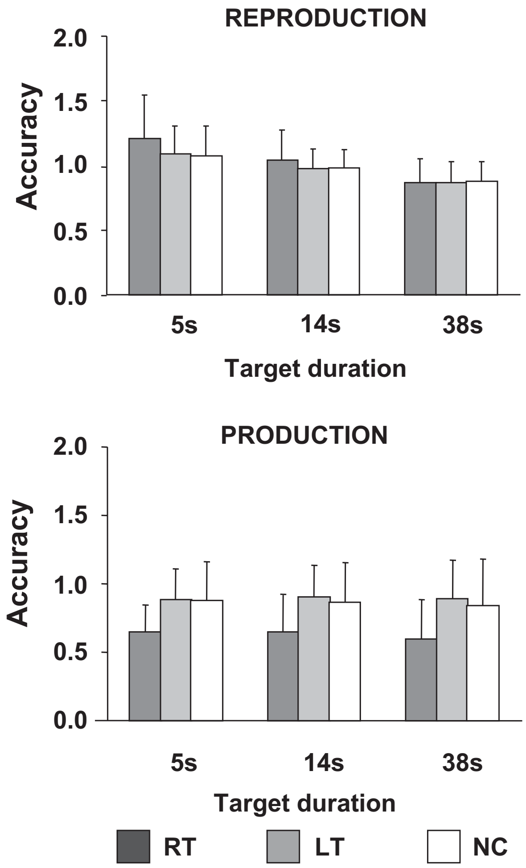

Fig. 6. Temporal accuracy (estimated duration/target duration) on the reproduction and production tasks, for the three target durations (5, 14, and 38 seconds) in temporal lobe resection patients and control participants.

patients produced durations significantly shorter than those produced by LT patients ($P<0.05$) and by NC participants ($P<0.05$). This is a robust finding, with consistent shorter productions being observed for all durations (Fig. 6).

Discussion and Conclusions

Patients with unilateral MTL resection performed like normal control participants in the reproduction of a previously encoded duration, whereas our study on AC amnesic patient showed impaired reproduction of durations (14 and 38 s) exceeding short-term memory capacity (as is usually reported). Considering the lesions of the patients, one could argue that reproduction deficits come from bilateral lesions, whilst unilateral medial-temporal lobe resection does not affect performance on reproduction tasks. Inversely, RT patients systematically underestimated durations in the production task. The production task requires associating a given duration with a representation of durations or with knowledge of conventional units. Therefore, we propose that overestimation in the RT patients' productions come from a distorted representation of these time units in long-term memory. This explanatory hypothesis is compatible with the spared ability to reproduce durations, since both phases of the task are timed with the same internal duration representation, even if this representation is distorted. On the other hand, the amnesic patient AC did not underestimate durations in the production task because, through procedural learning, he may have re-acquired the ability to correctly associate a given duration with his knowledge of conventional units.

In conclusion, the performance of the RT patients illustrated a dissociation in time estimation between relatively spared reproduction abilities and impaired production abilities. It seems that the preserved temporal lobe in patients with unilateral lesions is sufficient to perform the reproduction task as well as control participants. While amnesic patients generally exhibit severe long-term memory impairment, long-term memory disorders in RT patients are subtle. The right MTL may play a crucial role in translating duration, given in conventional units of time, into an accurate time production. These data provide further evidence of right hemisphere predominance in time estimation.

GENERAL DISCUSSION

Synthesis of the results of the five studies

Our work is the first one to compare temporal performance obtained in several groups of patients and healthy participants using duration reproduction and production tasks. These two tasks differently involve attention, memory and speed of information processing. In turn, these cognitive functions are differently affected in the various groups of subjects. Thus, the results allow us to characterize the relationships between cognitive deficits and impaired duration reproductions and productions in each group. Results obtained in the different experiments revealed that abilities and/or difficulties in duration reproductions or productions in the various groups of subjects were related to the preservation and/or impairment of attention, memory, and processing speed.

The underestimation of durations by elderly participants in the reproduction task performed in the concurrent reading condition arose from working memory deficits occurring with normal aging. The underestimation of durations by these subjects in the production task performed in the concurrent reading condition was due to the slowing of information processing with aging. These relationships have been assessed by the correlations observed between temporal performance in the two time--estimation tasks and scores on neuropsychological tests.

The impaired duration productions in patients with Parkinson's disease could result from L-Dopa medication. Indeed, a dopamine depletion is thought to induce a slower clock, leading to underestimation of time (Lange et al.1995b, Pastor et al. 1992). In our study, L-Dopa treatment would have induced the opposite effect, a faster clock, resulting in overestimation of durations. Alternatively, the short duration productions of the PD patients could be related to a short-term memory deficit, as suggested by the correlation analyses. It must be noticed that the duration reproductions of these patients did not differ from those of control participants (older adults). We obtained an opposite dissociation in the amnesic patient (AC) who exhibited long-term memory deficits and underestimated durations in the reproduction task. The underestimation of durations exceeding 10 to 15 seconds by the amnesic patient comes from episodic memory deficits, whereas the spared duration productions of the patient result from the preservation of the other memory systems and normal processing speed. The comparison of the two patterns of temporal performance is informative because in both cases, the under-and overestimation was particularly pronounced for the longest durations (Fig. 7).

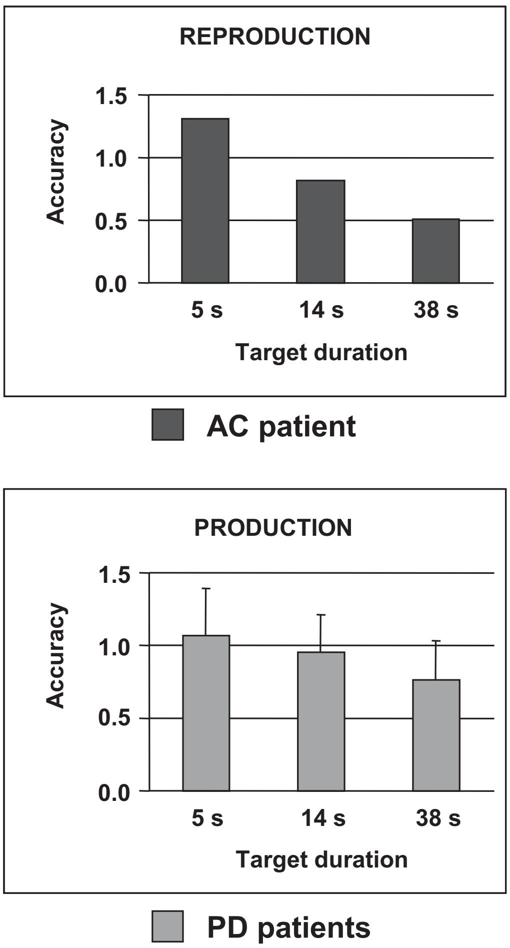

Fig. 7. Temporal accuracy (estimated duration/target duration) in the amnesic patient (AC) on the reproduction task and temporal accuracy in patients with Parkinson's disease on the production task.

The underestimation of all target durations, even the 5-second one, by patients with right medial temporal-lobe resections in the time-production task could come from a distorted representation of conventional time units (i.e., seconds) in long-term memory or from difficulty associating these conventional time units with the target durations. Thus, results suggest the involvement of medial temporal regions, particularly the hippocampus, in consolidating information in long-term memory and associating different information between them (Squire and Knowlton 1994). By contrast, the preserved duration reproductions in patients with either right or left medial temporal-lobe resections are likely due to the specificity of episodic memory deficits related to unilateral temporal lesions (Deweer et al. 2001, Jones-Gotman et al. 1997, Smith and Milner 1981). Whilst bilateral medial temporal lesions generally lead to a severe amnesia, unilateral resections would induce subtle episodic memory deficits without affecting the retrieval processes required for the reproduction of long durations.

The important temporal variability in patients with traumatic brain injury in the two time-estimation tasks is related to defective frontal functions. Indeed temporal variability has been previously reported in patients with frontal lesions (Casini and Macar 1999, Nichelli et al. 1995). In our study, the lack of precision of duration judgments appeared related to slowing down of processing speed. Moreover, this higher variability was even observed in the control counting condition. Consequently, we suggest that variability in traumatic brain injury patients is probably not specific to temporal information processing.

Contributions and limits

Some of these results are in agreement with those reported in literature, particularly the important underestimation of long durations by amnesic patients in the reproduction task (Kinsbourne and Hicks 1990, Richards 1973, Shaw and Aggleton 1994, Williams et al 1989), as well as the impairment of duration judgments in elderly subjects when time is estimated while performing a concurrent task (Block et al. 1998, Vanneste and Pouthas 1999). By contrast, other findings have not been previously reported. Kinsbourne and Hicks (1990) have shown that amnesic patients are able to produce one second duration. Our experiment generalized this result to the production of longer and more arbitrary durations, ones less often used in daily life. In addition, our study on patients with right medial temporal resections showed time estimation deficits restricted to the duration production task. Whereas several neuropsychological studies have suggested an involvement of both frontal and parietal cortex in temporal information processing (for a review see Harrington et al. 1998), only a few have investigated the contribution of medial temporal structures to time estimation. The experiments on patients with temporal lobe lesions indicated that such structures may be required for the estimation of durations in the second-range, particularly the right temporal structures.

Most studies on time estimation in elderly subjects have suggested that impaired duration judgments are related to either memory deficits or to slowing of information processing with normal aging. Our study has clarified the nature of these relationships by showing that the contribution of memory deficits and the slowing of processing speed in time estimation deficits depend on the temporal task used to collect temporal judgments.

Several studies have suggested that L-Dopa depletion slows down the rate of the internal clock and leads patients with Parkinson's disease to produce longer durations than control participants. In order to explain that medicated patients produced shorter duration than control participants, we proposed that L-Dopa treatment induced effects opposite to dopaminergic depletion on duration judgments, i.e., some kind of speeding up the clock.

To our knowledge, no study has investigated temporal performance in traumatic brain injury patients. Our results provide evidence that duration judgments in these patients, as in frontal patients, are characterized by important temporal variability. Our work strengthened the idea that temporal variability in traumatic brain injury patients could result from defective functions commonly thought to be controlled by the frontal cortex. These patients generally exhibit frontal dysfunctions (Adams 1984, Azouvi 2000). Furthermore a few studies have shown an important temporal variability in frontal patients (Casini and Ivry 1999, Nichelli et al. 1995). Finally, in studies on TBI and PD patients , variable duration judgments were related to working memory, a cognitive function generally known to be subtended by the frontal cortex (Baddeley 1996, Norman and Shallice 1986, Shimamura 2000). However, these relationships were not confirmed since frontal dysfunctions were not specifically investigated in the framework of our studies.

Cognitive functions in the duration reproduction and production tasks

Another way of considering the relationships that we have established between temporal performance and scores on neuropsychological tests is to see how they may help us to characterize the importance of information processing speed, memory and attention processes in the duration production and reproduction tasks. The pattern of results of our studies revealed slight differences from our predictions, but shed new light on the role of cognitive functions in these particular temporal tasks.

DURATION PRODUCTION AND PROCESSING SPEED

We predicted that processing speed, assumed to be related to the clock speed, would directly influence accuracy in duration productions. The results of the study examining age-related changes in time perception confirmed this hypothesis by revealing relationships between production accuracy and measures of processing speed. Indeed, subjects who produced the longer durations were those with the longest reaction times. Moreover, the processing speed measure (i.e., reaction time) was the best predictor of the age-related variance in production accuracy. This result is in agreement with the idea that the slowing of information processing with normal aging reflects the slowing of the internal clock rate (Cerella 1990, Salthouse 1994, Wearden et al. 1997) and would explain age-related changes in duration judgment (Craik and Hay 1999, Schroots and Birren 1990).

However, a relationship between duration production accuracy and processing speed (measured by the reaction time task) was not so clearly found in the experiments on TBI patients and PD patients. In traumatic brain injury patients, the slowing of information processing was related to an important temporal variability. In patients with Parkinson's disease, reaction times did not correlate with any time estimation indices. According to some authors (Boltz 1994, Denner et al. 1964), internal tempo is assumed to be a direct measure of internal clock speed. Therefore, we also used finger-tapping tasks with TBI patients and PD patients. The results showed that traumatic brain injury patients who produced longer durations in the concurrent reading condition were those with the slowest one-second tempo. Patients with Parkinson's disease who produced the longer durations in the control counting condition were those with the slowest one-second tempo (Table IV). These findings suggest that the production of a duration given in conventional time units (i.e., second) is related to the internal clock speed expressed *via* finger-tapping.

Table IV

Correlations between production accuracy and one-second motor-tempo in patients with traumatic brain injury (TBI) and with Parkinson's disease (PD)

	PRODUCTION	
	Control counting condition	Concurrent reading condition
TBI patients	0.39	0.66*
PD patients	0.59*	0.37

(*) $P<0.05$

DURATION PRODUCTION AND SHORT-TERM MEMORY AND WORKING MEMORY

Correlation analyses carried out in the study comparing temporal information processing in younger and older adults confirmed our hypothesis relative to a differential contribution of short-term memory and working memory in duration productions according to the condition in which the task is performed (Table V). In the control counting condition, short-term memory would allow participants to passively maintain the information until the identification of an appropriate response. By contrast, in the concurrent reading condition, working memory would be required in order to simultaneously manipulate temporal and non temporal information. However, the relationships seem to be more ambiguous, as shown by correlations obtained between duration productions in the concurrent reading condition and short-term memory scores in patients with Parkinson's disease (Table V). Thus the results indicate that duration production would require the subjects to maintain and manipulate information in memory.

Table V

Correlations between accuracy of duration productions and short-term and working memory scores

	PRODUCTION	
	Control counting condition	Concurrent reading condition
Younger and older participants		
Short-term memory	0.45*	-0.07
Working memory	0.29	-0.37
PD patients and control participants		
Short-term memory	-0.01	0.37*
Working memory	0.18	0.08

(*) $P<0.05$

DURATION REPRODUCTION AND SHORT-TERM AND WORKING MEMORY

Short-term and working memory would also be involved in duration reproductions. The ability to reproduce short durations by the amnesic patient is due to the fact that short-term memory is preserved. This patient was able to evaluate, to maintain in memory, and to reproduce durations when temporal information was processed in the short-term memory span. The correlations obtained in elderly subjects strengthened the relationship between short-term memory and duration reproductions. According to our hypothesis, the results of this study also revealed that working memory is involved in the reproduction task performed in the concurrent reading condition (Table VI).

DURATION REPRODUCTION AND EPISODIC MEMORY

The study conducted with the amnesic patient (AC), clearly showed that accurate reproductions of long du-

Table VI

Correlations between reproduction accuracy, short-term and working memory scores

	REPRODUCTION	
	Control counting condition	Concurrent reading condition
Younger and older participants		
Short-term memory	0.56*	0.15
Working memory	0.17	0.56*

(*) $P<0.05$

rations rely on a preserved episodic memory. However, the comparison between results obtained with AC and those obtained with patients with unilateral medial temporal-lobe resections suggests that accuracy for the reproduction of long durations is only affected when temporal lesions are bilateral, probably because memory is more severely affected. The involvement of episodic memory in the reproduction task is strengthened by the relationships between duration reproductions accuracy and scores on the Grober and Buschke test (Grober and Buschke 1987) obtained in older adults (Table VII). According to our hypothesis, episodic memory would be necessary to reproduce durations exceeding 10-15 seconds. The delay introduced between the encoding and reproduction phases would require a retrieval of information from long-term memory, when the target duration exceeds the short-term memory span. In the amnesic patient (AC)

Table VII

Correlations between accuracy of duration reproduction and episodic memory scores

	REPRODUCTION					
	Control counting condition			Concurrent reading condition		
	5 s	14 s	38 s	5 s	14 s	38 s
Younger and older participants						
Free recall	0.21	0.2	0.07	0.39*	0.55*	0.42*
Delayed free recall	0.18	0.04	-0.01	0.32*	0.50*	0.43*

(*) $P<0.05$

as well as in elderly subjects, the underestimation of long durations reflects a defective retrieval of information in episodic memory.

DURATION PRODUCTION AND EPISODIC MEMORY

We assumed that episodic memory was not necessary in the production task, as was initially suggested by Kinsbourne and Hicks (1990). This appears to be corroborated by the results obtained in the amnesic patient (AC) who was able to produce durations in the range of several seconds despite a selective deficit of episodic memory. Some other results of our work suggested that the episodic memory system might be required in the duration production task. Thus patients with right temporal-lobe resections, who generally exhibit specific episodic memory deficits, produced shorter durations than control participants. The study on elderly subjects also revealed correlations between episodic memory scores (Grober and Buschke test) and production accuracy, especially when the task was performed in the concurrent reading condition. But the role of episodic memory in these two cases appears difficult to explain.

GENERAL CONCLUSIONS

The five studies revealed that the relationships between time estimation and cognitive functions – processing speed and memory – depend on the context in which duration is evaluated. Temporal dysfunctions in healthy elderly subjects and different brain-damaged patients indicated that these relationships may be specific either to the time-estimation task, to the condition in which the task is performed, or to the range of the target durations. The results obtained in the same conditions for different groups of participants emphasize the complex interaction between both cognitive and contextual factors involved in time estimation.

Therefore, it seems important to consider such complexity in the theoretical framework of psychological time models. The role of different components of these models – clock, memory, and decision – may vary depending on the temporal context and the population. Thus our studies help to clarify the nature of reference memory initially described in Church's model (1984) by showing differential involvement of episodic memory depending on the time-estimation task and the length of the duration to be estimated.

The major aim of our work was to determine the relationships between cognitive impairments and loss of accuracy and/or precision in duration judgments. Our studies focus mainly on the clock and memory components of the temporal information processing model (Wearden 2004). Further studies should investigate the relationships between duration judgments and executive functions within various groups of patients, particularly those presenting with frontal dysfunction. It would also be interesting to determine the influence of residual cognitive capacities of patients which could lead them to use compensatory strategies. We do know how difficult it can be to tackle this last issue which requires individual investigations and introspective methods. However, such studies could help assess the role of decisional mechanisms in duration judgments and thus provide a more complete picture of relationships between cognitive functions and the different processes involved in time estimation.

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