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Time estimation by patients with frontal lesions and by Korsakoff amnesics

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Abstract

We studied time estimation in patients with frontal damage (*F*) and alcoholic Korsakoff (*K*) patients in order to differentiate between the contributions of working memory and episodic memory to temporal cognition. In Experiment 1, *F* and *K* patients estimated time intervals between 10 and 120 s less accurately than matched normal and alcoholic control subjects. *F* patients were less accurate than *K* patients at short ($<$ 1 min) time intervals whereas *K* patients increasingly underestimated durations as intervals grew longer. *F* patients overestimated short intervals in inverse proportion to their performance on the Wisconsin Card Sorting Test. As intervals grew longer, overestimation yielded to underestimation for *F* patients. Experiment 2 involved time estimation while counting at a subjective 1/s rate. *F* patients' subjective tempo, though relatively rapid, did not fully explain their overestimation of short intervals. In Experiment 3, participants produced predetermined time intervals by depressing a mouse key. *K* patients underproduced longer intervals. *F* patients produced comparably to normal participants, but were extremely variable. Findings suggest that both working memory and episodic memory play an individual role in temporal cognition. Turnover within a short-term working memory buffer provides a metric for temporal decisions. The depleted working memory that typically attends frontal dysfunction may result in quicker turnover, and this may inflate subjective duration. On the other hand, temporal estimation beyond 30 s requires episodic remembering, and this puts *K* patients at a disadvantage. (*JINS*, 2000, *6*, 517–528.)

Keywords: Time estimation, Duration, Korsakoff syndrome, Frontal lobe, Amnesia, Working memory, Episodic memory

INTRODUCTION

The sense of time passing is fundamental to human consciousness and to the sequential structuring of activities of everyday life. However, this sense is not directly perceived through any amodal sensor or receptor surface of its own; on the contrary, the ability to estimate time must be inferred from other sources of information. Our subjective sense of time passing is either based on memory for previous events that occurred during a particular time interval or it is read off an internal clock-like device in the brain (or both).

Studies have shown that brain areas, lesions of which may impair episodic and working memory in amnesic and prefrontal syndromes, are also implicated in time estimation. Because of episodic memory problems amnesic patients are inaccurate in estimating temporal duration. On verbal time estimation measures, in which participants estimate elapsed time in seconds, amnesics underestimate time intervals (Kinsbourne & Hicks, 1990; Nichelli et al., 1993; Williams et al., 1989). This suggests that temporal estimation depends upon the retrieval of events that occurred during the time intervals. However, Shaw and Aggleton (1994) found temporal duration judgment and memory ability to be unrelated. They described patients with amnesia related to herpes encephalitis who were unimpaired in time estimation. They also found negative correlations between memory performance and accuracy of temporal estimation in Korsakoff amnesics. Other inconsistencies concern whether amnesia is associated with under- or overestimation of time intervals. While most amnesics underestimate time, some are prone to overestimation (for example, case B.B. in Nichelli

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et al., 1993). There is little information regarding variables that determine whether amnesics under- or overestimate time.

In addition to memory, processes that mediate duration estimation include decisional mechanisms for which frontal–executive functions play a crucial role (Fuster, 1989). Prefrontal lesions interfere with timing in animals (Glickstein et al., 1964; Meck et al., 1984) and humans (Bruyer & Bontemps-Devogel, 1979). Single unit recordings in monkeys reveal firing in frontal brain regions that correlates with task-relevant temporally separated events (Fuster, 1993; Niki & Watanabe, 1979). In the neuropsychological literature, patients have been reported who demonstrate time estimation problems within the context of damage to frontal systems. An amnesic patient (case B.B.) reported by Nichelli et al. (1993), who overestimated time, had severe frontal impairment. Nichelli and colleagues speculated that overestimation of time by amnesic patients with frontal damage resulted from differential impairments in working and reference memory. A negative correlation between magnitude of time estimation and performance on a test of cognitive estimation thought to assess frontal functions in Korsakoff and alcoholic participants has been viewed as further evidence for the role of frontal systems in time estimation (Shaw & Aggleton, 1994).

In this study we examined the relationships between memory, frontal–executive functions, and temporal estimation by comparing patients with frontal damage (*F*) and Korsakoff amnesic patients (*K*). Duration estimation may be influenced by numerous, qualitatively different, factors including expectancy, experience, task difficulty, fatigue, impatience, and boredom (Kinsbourne, in press). We set up experimental conditions in which such factors could be minimized. In Experiment 1, verbal estimations of filled time intervals were recorded. In this past time condition participants were reminded before each trial that they would be asked to estimate its duration. In Experiment 2, we used a measure for present time passing (cf. Kinsbourne & Hicks, 1990). Participants counted at a subjective 1/s rate without interference; the rate at which they counted was considered an index of their internal tempo of time passing. In Experiment 3, a duration production task was used. Participants performed the same activity as in Experiment 1, but in this condition they indicated when a previously stipulated time period had elapsed. Performance in the three experiments was correlated with performance on neuropsychological tests.

EXPERIMENT 1

Methods

Research participants

Four groups of male participants were studied; 8 *F* patients, 8 *K* patients, 8 normal controls (*N*), and 8 non-Korsakoff alcoholic controls (*A*). *F* and *K* patients were recruited from outpatient and inpatient clinics at the Boston VA Hospital and the Edith Norse Rogers Memorial VA Hospital. Patients were referred by their neurologists and psychologists. Patients with depression, psychosis, and/or dementia were excluded from the study. All *F* patients demonstrated attention and executive dysfunction on neuropsychological testing. Their mean age was 53.6 (range 21–64) and their mean education was 12.3 (range 6–20) years. *F* patients were compared to *N* participants whose mean age and education were matched to *F* patients. In the other grouping *K* patients were compared to *A* participants. All *K* patients were in a chronic (more than 1 year postonset) and stable condition and had severe anterograde amnesias associated with some degree of retrograde amnesia. Talland (1965) introduced the practice of controlling *K*s' performance with nonamnesic alcoholic contrast group. Alcoholism itself incurs risk of significant neuropsychological deficits (Glenn & Parsons, 1991); hence, the choice of an *A* group assures that any deficient performance of *K* patients is not due to alcoholism alone and that participants differ only with respect to their episodic memory skills. The mean age of *K* patients was 53.2 (range 40–64) years and their mean education was 11.4 (range 8–20) years. The mean age and education of *A* participants were carefully matched to *K* patients.

Etiology and side of lesion of *F* patients and performance on neuropsychological tests of *F* and *K* patients, including WAIS–R (Wechsler, 1981), Wisconsin Card Sorting Test (WCST; Grant & Berg, 1948), and Wechsler Memory Scale–Revised (WMS–R; Wechsler, 1987) are presented in Table 1. As can be seen, *K* patients had significant memory problem as indicated by their impairment on delayed memory indices from the WMS–R. With a few exceptions, patients from *F* and *K* groups performed poorly on the WCST, a test presumed to reflect the integrity of frontal networks (Weinberger et al., 1986). It should be noted that studies have shown that there is much variability between frontal patients in the degree of WCST impairment (Anderson et al., 1990). This was also the case in the present frontal sample. Similarly, the comorbidity of impaired performance on WCST in our *K* patients is consistent with the literature that demonstrated the occasional but not pervasive presence of frontal dysfunction in Korsakoff amnesics (Kopelman, 1991; Wiegersma et al., 1991).

Procedure: Verbal time estimation

In this prospective verbal estimation paradigm participants were warned before each trial that they would be asked to estimate how long the trial had lasted. Participants sat facing the computer monitor in a semidarkened room. During each trial, they were required to read numbers (*1*–*9*) aloud in order to prevent subvocal counting. Number stimuli were presented in random sequence on the monitor throughout each predetermined interval. The rate of stimulus presentation was variable and was predetermined regardless of participant's response rate. Stimulus presentation and timing were controlled by the HyperCard® software package (Apple Computer Inc., 1987).

Table 1. Scores on neuropsychological tests of intelligence, attention and frontal–executive function, and memory in the two patient groups

			WAIS		WCST		WMS–R		Digit span	
Case	Etiology	Lesion side	VIQ	PIQ	Cat.	% Persev.	Att.	Del.	F	B
Frontal group										
G.A.	Benign tumor	R	78	77	3	82	78	80	5	3
M.S.	Head injury	Bil. (R > L)	84	76	2	90	76	74	6	3
G.H.	Infarct	Bil. (R > L)	89	74	3	53	87	71	7	4
D.F.	Benign tumor	Bil. (R > L)	93	103	0	74	77	93	5	3
S.Z.	Hemorrhage	L	101	101	5	20	84	80	4	3
Y.I.	Benign tumor	Bil. (R > L)	121	115	6	8	108	90	7	4
S.K.	Infarct	R	107	86	1	70	84	107	7	4
M.Y.	Infarct	L	106	100	2	42	94	102	8	4
Korsakoff group										
Y.U.			103	92	3	30	112	50	7	4
S.O.			106	90	5	10	104	70	6	6
L.B.			87	98	3	18	93	65	7	4
G.P.			123	118	6	12	116	56	8	6
R.D.			83	83	2	36	99	50	6	3
R.L.			—	—	6	12	83	51	6	5
T.Y.			85	72	1	44	89	50	6	4
M.T.			84	82	3	28	75	60	6	4

Note. Att.: attention–concentration index, B: backward, Bil.: bilateral, Cat.: categories achieved, Del.: delayed recall index, F: forward, L: left, % Persev.: % perseverative errors, R: right.

Time intervals were 10, 30, 60, 90, and 120 s. Each time interval was presented four times in a random sequence of 20 trials. At the beginning of the task, participants were instructed to estimate how many seconds each trial had taken. At the conclusion of each trial, the monitor presented the sentence, "What is your answer?" Participants were expected to say how long the interval was in seconds.

Results

Figure 1 depicts the mean deviation from actual time of the four groups irrespective of direction of error (under- or overestimation) for each time interval. This is the absolute value of the difference between subjectively estimated time and the actual time at each interval. Analyses of variance (ANOVAs) were conducted separately for *F* patients *versus N* participants and for *K* patients *versus A* participants.

A Between-Group (*F vs. N*) × Interval (10–120 s) repeated measures ANOVA revealed a significant main effect of group [$F(1,14) = 4.46$, $p < .05$] as well as interval [$F(4,56) = 7.68$, $p < .0001$]. *F* patients were less accurate than *N* participants, and accuracy diminished as intervals increased. The Group × Interval interaction, however, was not significant ($p > .10$), indicating that *F* patients were less accurate in this condition throughout the intervals.

The other Between-Group (*K vs. A*) × Interval (10–120 s) repeated measures ANOVA revealed a significant main effect of group [$F(1,14) = 18.51$, $p < .001$] as well as interval [$F(4,56) = 23.12$, $p < .0001$]. A Group × Interval interaction was significant [$F(4,56) = 5.05$, $p < .05$]. *K* patients were less accurate as intervals became longer.

The performances of *F* and *K* patients were compared by a 2 (group) × 5 (interval) repeated measures ANOVA. The main effect of interval was significant [$F(4,56) = 11.52$, $p < .0001$] while group was not ($p > .10$). Importantly, the Group × Interval interaction was significant [$F(4,56) = 2.43$, $p < .05$]. *F* patients were less accurate than *K* patients at shorter intervals. Conversely, at longer intervals *K* patients were less accurate than *F* patients.

Linear regression analyses between actual time and magnitude of errors were significant for all the four groups. However, the slope across time was greater for *K* patients (24°) than for the other three groups. The slopes for *N* participants (11°), *F* patients (12°), and *A* participants (12°) were comparable.

Figure 2 depicts each patient's performance in the *F* and *K* groups separately relative to the actual time elapsed. Among *F* patients (Figure 2, left), there were both under- and overestimators, there being more of the latter, but both increased their estimates with increased actual time. For *K* patients (Figure 2, right), performances at 10 and 30 s were variable, but they showed curtailed estimation after 30 to 60 s, so that all patients underestimated at 120 s.

Scores for performance on verbal time estimation tasks were examined in relation to performance on tests of intelligence, attention and frontal–executive functions, and memory. Table 2 shows the results for *F* and *K* patients, analyzed separately. For both *F* and *K* groups, estimated time was

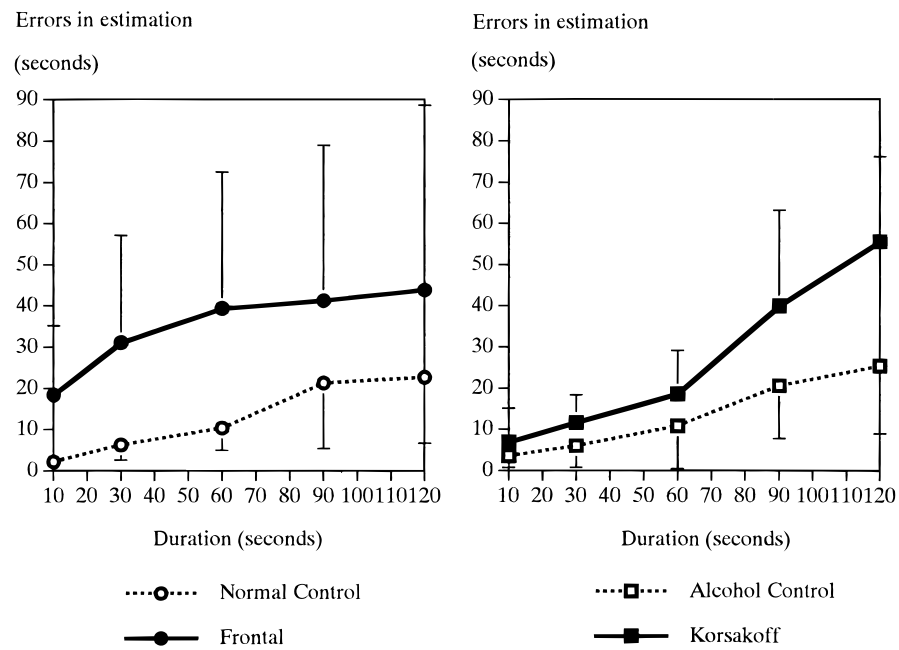

Fig. 1. Mean error from the target for each time interval in the verbal time estimation (left, frontal patients and normal controls; right, Korsakoff patients and alcoholic controls).

negatively correlated with the number of categories achieved and positively correlated with the number of perseverative errors on the WCST (significantly for intervals below 60 s). The significant correlations of estimated time with WCST categories and perseverative errors remained even when the effects of memory and intelligence were partialed out. The correlations between WCST categories and perseverations were $-.78$ ($p < .01$) for *F* patients and $-.88$ ($p < .01$) for *K* patients. Estimates for intervals longer than 60 s correlated positively with WMS–R delayed memory score in the *F* group only.

Delayed memory scores were not correlated with time estimation in *K* patients. The only correlation between the WAIS–R and time estimation that was significant was a negative correlation at 30 s in *K* patients.

Discussion

The *N* and *A* control groups demonstrated the expected linear increases in estimates with increasing actual time. There was no inflection in the curve to mark the transition between shorter and longer intervals (Michon, 1975; Water-

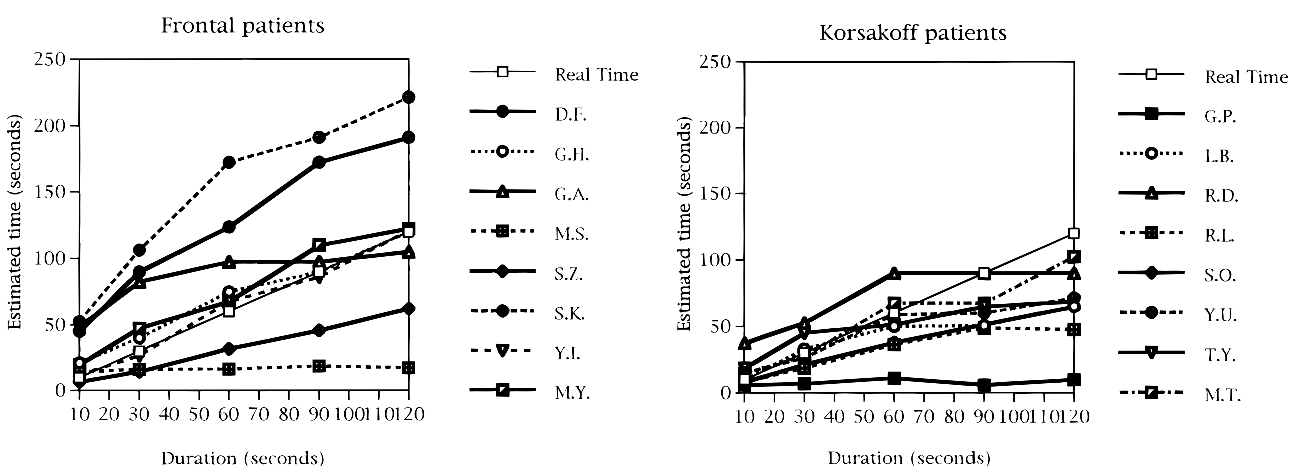

Fig. 2. Estimated time as a function of under/overestimation for each time interval in the verbal time estimation (left, frontal patients; right, Korsakoff patients).

Table 2. Correlations between estimated time in verbal time estimation and neuropsychological performance in the two patient groups

	WAIS–R		WCST		WMS–R	
Group	VIQ	PIQ	Cat.	% Persev.	Att.	Del.
Frontal group ($N = 8$)						
10 s	−.29	−.22	−.67*	.63*	−.45	.43
30 s	−.13	−.09	−.67*	.50	−.33	.58
60 s	−.10	−.04	−.54	.28	−.10	.66*
90 s	−.20	−.20	−.59	.19	−.03	.75*
120 s	−.28	−.25	−.48	.06	.10	.73*
Korsakoff group ($N = 8$; VIQ and PIQ, $N = 7$)						
10 s	−.52	−.56	−.62**	.74*	−.09	−.47
30 s	−.75*	−.75*	−.63*	.79**	−.23	−.34
60 s	−.58	−.52	−.52	.57	−.17	−.34
90 s	−.63	−.61	−.50	.34	−.40	−.29
120 s	−.66	−.61	−.45	.33	−.49	.01

$^{*}p < .05$. $^{**}p < .01$.
Note. Att.: attention–concentration index, Cat.: categories achieved, Del.: delayed recall index, % Persev.: % perseverative errors.

worth, 1985). Both *F* and *K* patients were less accurate than their control groups, and the estimates of both across time deviated from linearity. *F* patients deviated more from actual time than did *K* patients at the shorter intervals, whereas at longer intervals *K* patients were less accurate. At the shorter intervals *F* patients tended to overestimate and at the longer intervals *K* patients underestimated. At the shorter intervals, some *K* patients underestimated and others overestimated time, so that the group mean estimates approximated those of *A* participants but with far greater variance. By definition, amnesics have selective deficits in long term (episodic) memory with short term memory remaining relatively intact (Baddeley & Warrington, 1970; Talland, 1965). When the time intervals were longer, *K* patients uniformly underestimated time consistent with previous findings that amnesics curtail time estimations for durations that exceed the time frame of short-term memory (Kinsbourne & Hicks, 1990).

Both *F* and *K* patients overestimated short time intervals in association with their WCST performances. The fewer categories they achieved and the higher their perseverative score on the WCST, the more likely were *F* and *K* patients to overestimate short time durations. These difficulties may imply depleted working memory, which may inflate subjective estimation of very short intervals (see General Discussion). Another simpler explanation for overestimation of 10 s is that it is generally difficult to underestimate such short intervals. Also, for *F* patients, the more their long term memory was impaired, the more they underestimated the intervals. The same relationships existed in *K* patients, but fell short of significance. This lack of significance may be due to *K* patients' near-floor performance on the delayed index.

EXPERIMENT 2

Time estimation involves referencing an experienced duration to an internal metric that is composed of second-long intervals. Erroneous estimates can be due to either an experience that subjectively seems longer or shorter than its actual duration, or to a reference metric that is systematically extended (making for underestimates) or contracted (making for overestimates). To assess the integrity of the reference system (i.e., the participants' notion of the duration of its unit), we performed a task of present time estimation with the same participants.

Methods

Research participants

The same patient and control groups as in Experiment 1.

Procedure: Present time estimation

Participants were instructed to count silently at a 1/s rate from the examiner's *start* to *stop* signal. No distractor tasks were used. Intervals were identical to these in Experiment 1, namely, 10, 30, 60, 90, and 120 s. Each time interval was presented twice in random sequence, using a stopwatch.

Results

Figure 3 depicts the mean deviation from actual time of the four groups irrespective of direction of error (under- or overcounting) for each time interval in the 1/s counting task. For *F* patients, a Between-Group (*F vs. N*) × Interval (10–120 s) repeated measures ANOVA did not yield a main ef-

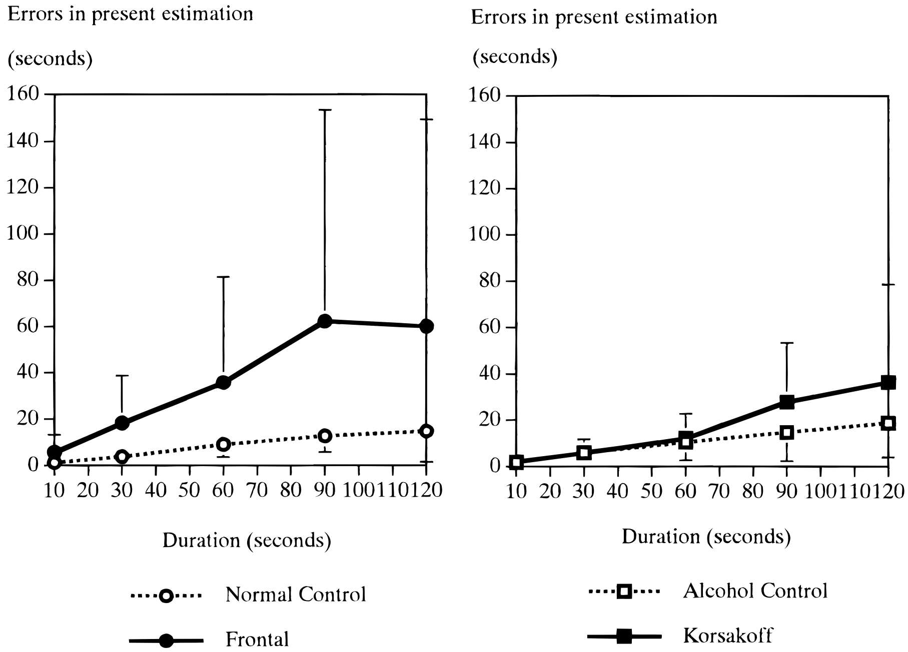

Fig. 3. Mean error from the target for each time interval in the present time estimation (counting condition; left, frontal patients and normal controls; right, Korsakoff patients and alcoholic controls).

fect of group ($p > .10$). A main effect of interval was significant [$F(4,56) = 4.66$, $p < .01$], but a Group × Interval interaction was not ($p > .10$). Although *F* patients appeared to be less accurate as intervals became longer, differences between the two groups did not reach significance because of *F* patients' great variability.

For *K* patients, another 2 (group) × 5 (interval) repeated measures ANOVA only yielded a main effect of interval, indicating that *K* and *A* groups were equivalent throughout the intervals.

Linear regression analyses between actual time and magnitude of errors yielded significant slopes for all four groups. However, the slope was greater for *F* patients (28°) than for *N* participants (7°) and *A* participants (9°). The slope for *K* patients (18°) was intermediate.

Figure 4 depicts the direction of present time estimation by counting in *F* and *K* patients. In *F* patients, remarkable overcounting was observed in 1 patient (G.A.). Except for G.A., the performance of *F* patients was relatively intact although most tended to overcount. *K* patients did not show bias to over- or undercount, and as was demonstrated in the magnitude of errors, the ability to count at a 1/s rate in *K* patients was not impaired relative to control (cf. Kinsbourne & Hicks, 1990).

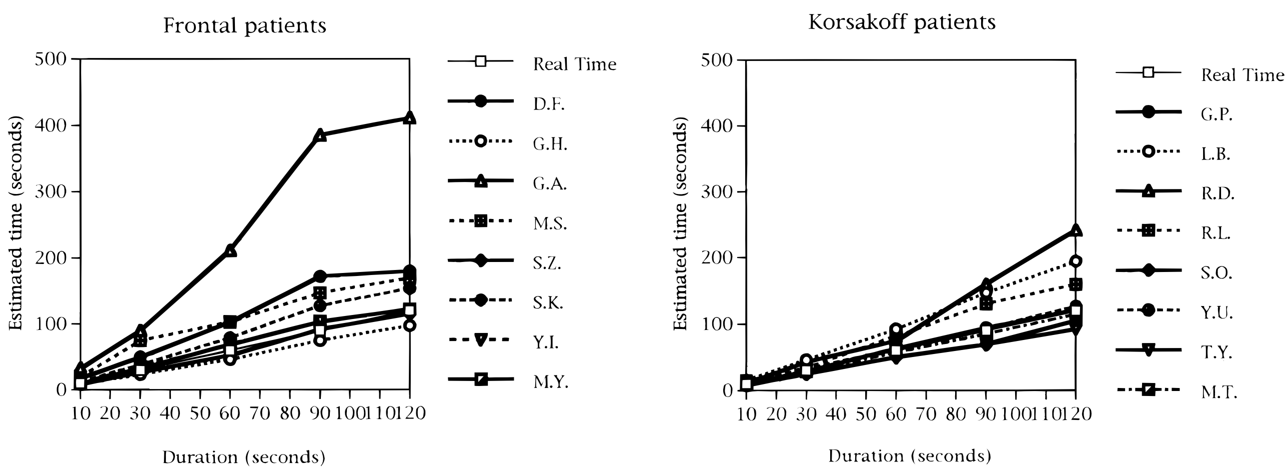

Fig. 4. Estimated time as a function of under/overestimation for each time interval in the present time estimation (counting condition; left, frontal patients; right, Korsakoff patients).

The topic of interest in this research was the subjective sense of time passing, independent of the units in which time was measured. The results of Experiment 2 showed that systematic deviations from veridicality in the time estimates of F and K patients could not be explained by deviations in reference standards. However, there was some overcounting on the part of F patients. In order to correct for this slight deviation in self-paced counting, we examined the estimates obtained in Experiment 1 in relation to the rate of counting in Experiment 2. Estimates in Experiment 1 were divided by those in the present time condition at each time interval.

The results are shown in Figure 5. Scores above 1.0 represent overestimation and those below 1.0 underestimation. The proportional estimation scores were analyzed with a Between-Group (F *vs.* N) $\times$ Interval (10–120 s) repeated measures ANOVA. A main effect of interval was significant [$F(4,56) = 7.84$, $p < .0001$]. A main effect of group did not reach significance ($p > .10$). Importantly, however, a significant Group $\times$ Interval interaction was obtained [$F(4,56) = 8.46$, $p < .0001$]. Contrast of means demonstrated that F and N groups differed at the 10-s duration [10 s, $p < .001$; 30–120 s, $p > .10$]. In N participants, the proportional estimation score was around 1.0 throughout the intervals. In contrast, F patients overestimated 10 s and tended to overestimate 30 s.

For K patients, a 2 (group) $\times$ 5 (interval) repeated measures ANOVA demonstrated a significant main effect of interval [$F(4,56) = 10.39$, $p < .0001$]. A main effect of group was not significant ($p > .10$). However, a significant Group $\times$ Interval interaction [$F(4,56) = 2.36$, $p < .05$] indicated that K patients underestimated longer intervals. Contrast of means demonstrated a significant difference between K and A groups only at 120 s [10–90 s, $p > .10$; 120 s, $p < .05$].

Scores for second-by-second time estimation were correlated with performance on tests of intelligence, attention and frontal–executive function, and memory. The correlations between estimated time and neuropsychological variables were insignificant both for F and K patients, except that perseverative errors on WCST and estimated time for 30 s correlated significantly in F patients ($r = .72$, $p < .05$).

Correlations between proportional time estimates and WCST scores were also computed. In a combined group of F and K patients ($N = 16$), proportional estimation scores at shorter durations tended to correlate negatively with categories achieved (10 s, $r = -.67$, $p < .001$; 30 s, $r = -.62$, $p < .001$; 60–120 s, $p > .05$) and positively with perseverative errors (10 s, $r = .47$, $p < .05$; 30 s, $r = .40$, $p < .05$; 60–120 s, $p > .05$) on WCST.

Discussion

F patients overestimated time even in the present time condition, in that they counted seconds more quickly than normal controls. This accelerated time pacing may be associated with an impulsive cognitive style of some patients and may partially account for overestimation of past time. However, this accelerated pacing did not fully account for F patients' past time overestimation at intervals of 10 and 30 s since proportional estimation scores were above 1.0. K patients

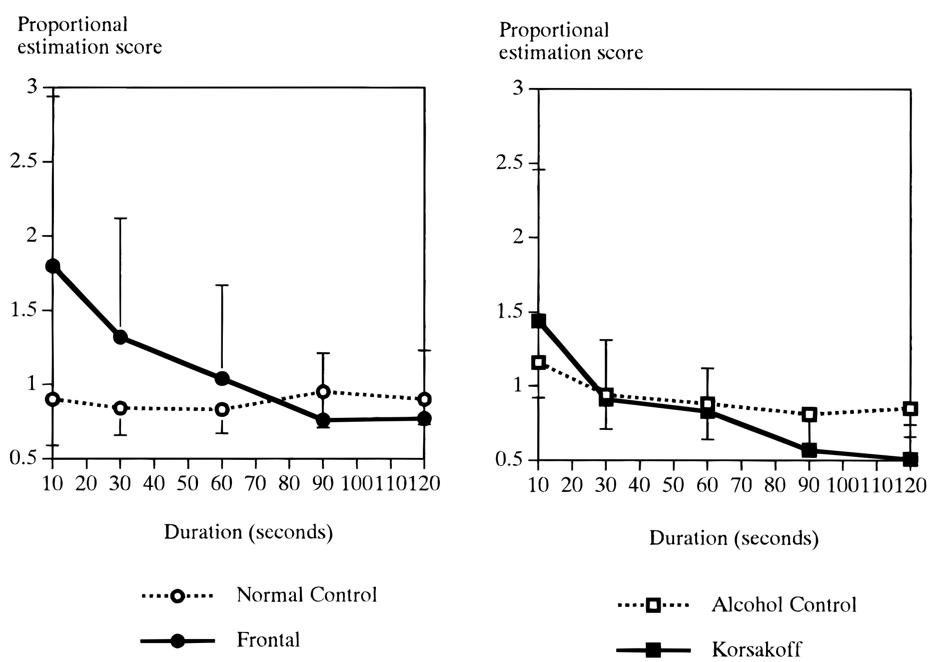

Fig. 5. Proportional estimation score (verbal estimation/self-paced counting) (left, frontal patients and normal controls; right, Korsakoff patients and alcoholic controls).

demonstrated a similar but markedly down-sloping curve as interval increased beginning at 60 s. In contrast, their estimations were relatively intact at shorter intervals. This shape of the curve was reported for *K* patients by Kinsbourne and Hicks (1990).

EXPERIMENT 3

In Experiment 3, we used a contrasting task, in which participants self-produced specified intervals in order to determine whether there is a relationship between verbal estimation and production of the same time intervals.

Methods

Research participants

The two patient groups and the two control groups were the same as those in Experiments 1 and 2.

Procedure: Time production

Subjects performed the same tasks as in Experiment 1, but on this occasion they were asked to indicate when they thought a predetermined time interval was over. In this sense they were producing rather than estimating time intervals. Time intervals and the number of trials were the same as in Experiment 1. The instruction, "Please click the mouse when you think the time is up," was always present on the computer screen, and a card that indicated each interval was placed before the participant to enable him to keep the task in mind.

Results

Figure 6 depicts the mean deviation from actual time of the four groups irrespective of direction of errors (under- or overproduction) for each time interval in the duration production. Separate ANOVAs were conducted for *F* and *K* patients as in Experiments 1 and 2. Between *F* and *N* groups, main effects of group $[F(1,14) = 5.45, p < .05]$ and interval $[F(4,56) = 2.45, p < .06]$ were significant, but a Group $\times$ Interval interaction was not ($p > .10$). *F* patients were less accurate in the duration production throughout the intervals. However, differences between the performance of *F* and *N* groups at short intervals were less prominent than in verbal time estimation. Specific contrast of means yielded a significant difference between *F* and *N* groups only at 60 s ($p < .05$).

An ANOVA for *K* and *A* groups demonstrated significant main effects of group $[F(1,14) = 4.09, p < .05]$ and interval $[F(4,56) = 8.96, p < .001]$ and a Group $\times$ Interval interaction $[F(4,56) = 3.02, p < .02]$, indicating that *K* patients were selectively impaired in duration production at longer intervals. Contrast of means indicated that performances of *K* and *A* groups were identical at intervals 10 and 30 s ($p > .10$), marginally different at 60 s ($p = .06$), and significantly different at 90 ($p < .05$) and 120 s ($p < .01$).

Linear regression analyses between actual time and magnitude of errors were significant for all the four groups. The

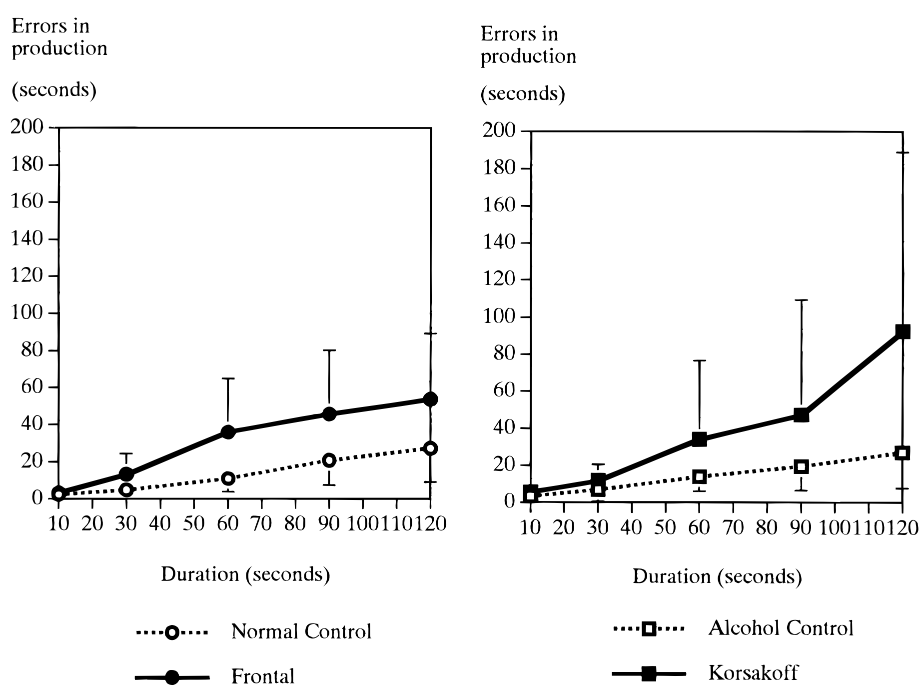

Fig. 6. Mean error from the target for each time interval in the time production (left, frontal patients and normal controls; right, Korsakoff patients and alcoholic controls).

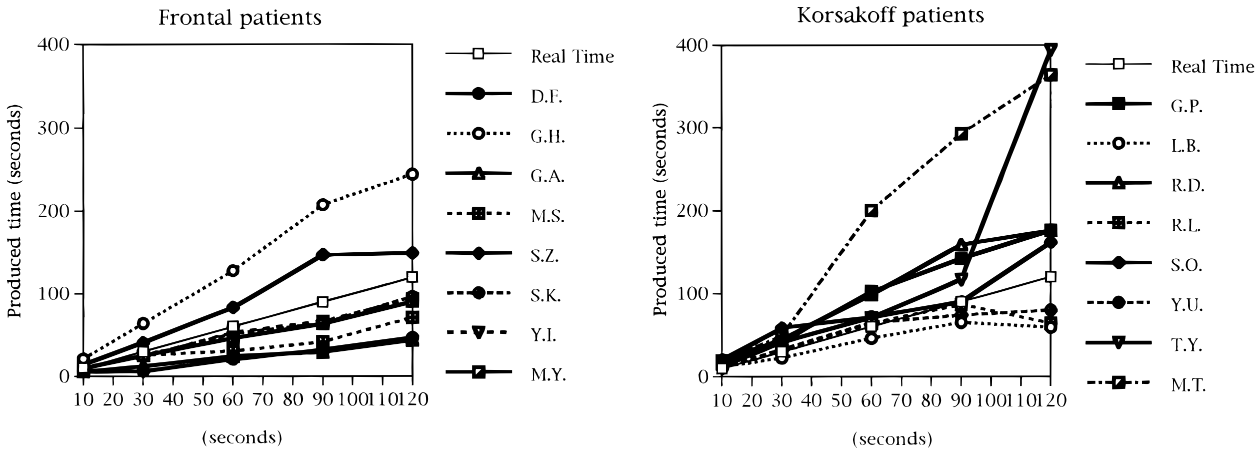

Fig. 7. Produced time as a function of under/overproduction for each time interval in the time production (left, frontal patients; right, Korsakoff patients).

slope for *K* patients (37°) was steeper than for *F* patients (25°); the slope for *F* patients was steeper than for *N* (14°) and *A* (12°) participants.

Figure 7 depicts the performance of self-produced time intervals in *F* and *K* patients. Among *F* patients, severe overproduction of time was observed in two patients (S.Z. and G.H.). Five patients tended to underproduce intervals. Production of *K* patients was also variable with some underestimates and some overestimates. As with the magnitude of errors, production in *K* patients was preserved at short intervals, but most *K* patients overproduced time as the interval increased. Two patients (T.Y. and M.T.) grossly overproduced the 120-s condition. In contrast, three patients showed underproduction (L.B., R.L., and Y.U.), as they also did in the verbal time estimation.

In order to correct the self-produced intervals for the subjective experience of present time, a proportional production score was computed, as in Experiment 1. Performance in the time production condition was divided by self-paced estimation in the present time condition at each time interval. The results are shown in Figure 8. Scores above 1.0 represent relative overproduction and those below 1.0 underproduction. The proportional production scores for *F* and *K* patients were analyzed separately.

First, a Group (*F vs. N*) $\times$ Interval (10–120 s) repeated measures ANOVA was computed. A main effect of interval

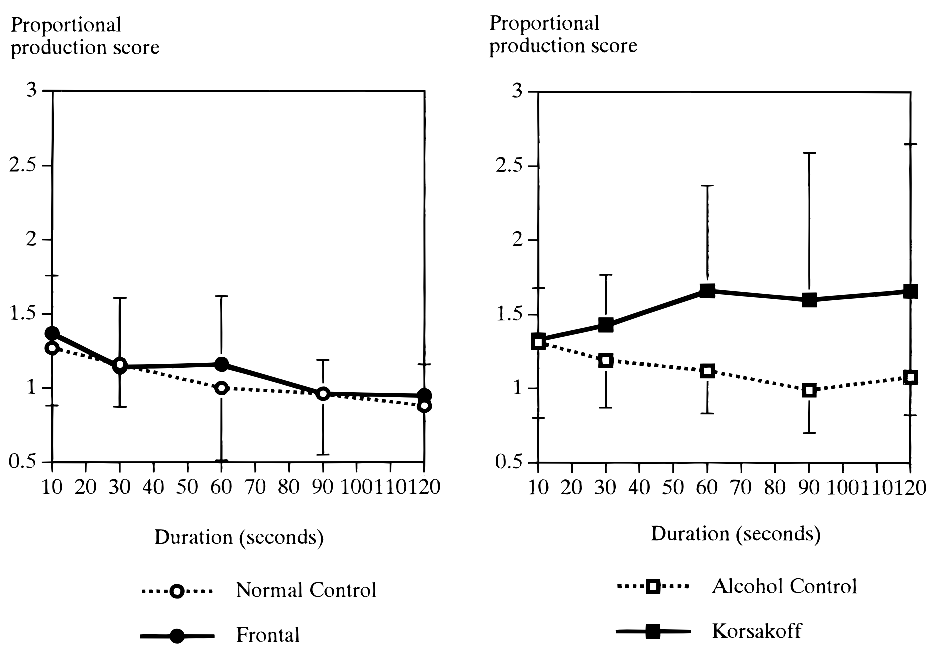

Fig. 8. Proportional production score (time production/self-paced counting) (left, frontal patients and normal controls; right, Korsakoff patients and alcoholic controls).

was significant $[F(4,56) = 7.28, p < .0001]$. However, a main effect of group ($p > .10$) and a Group × Interval interaction ($p > .10$) did not reach significance. Contrast of means demonstrated that *F* and *N* groups did not differ at any of the intervals examined. Proportional production scores of *F* patients as a group were comparable to those of *N* participants.

For *K* patients, a 2 (group) × 5 (interval) repeated measures ANOVA demonstrated a significant main effect of group $[F(4,14) = 4.33, p < .05]$. A main effect of interval ($p > .10$) and a Group × Interval interaction ($p > .10$) did not reach significance. *K* patients tended to overproduce time as intervals increased, although the contrast of means failed to demonstrate a reliable difference between *K* and *A* groups at any intervals.

The produced time in Experiment 3 was correlated with the estimated time in Experiment 1 in order to see whether there was any inverse correlation between the performance at the two tasks. The results are shown in Table 3. If we combine the four groups together, there were weak inverse correlations throughout the intervals between the two tasks. In *F* patients, these inverse correlations were significant only at short intervals. However, *K* patients did not show any significant correlations at any intervals.

Scores for time production were correlated with performance on tests of intelligence, attention and frontal–executive functions, and memory. In both *F* and *K* patients, correlations between produced time duration and intelligence, attention, and memory variables were not significant. In a combined group of *F* and *K* patients ($N = 16$), perseverative errors on WCST correlated negatively with produced durations at short intervals (10 s, $r = -.61$, $p < .01$; 30 s, $r = -.60$, $p < .01$; 60 s, $r = -.52$, $p < .05$; 90–120 s, $p > .10$). So those participants who appeared to be most frontally impaired tended to be the ones who underproduced at short intervals—a result to be expected since these were the participants who most overestimated in Experiment 1.

Discussion

Temporal duration judgments of *K* patients were inaccurate at intervals beyond 1 min both in verbal estimation (Experiment 1) and in production (Experiment 3). As duration increased, *K* patients tended to underestimate in the verbal condition. In production, the direction of errors was variable with under- and overestimators, so that the produced time did not show significant correlations with the verbally estimated time. However, the proportional production scores for *K* patients tended to show overproduction as intervals increased. As with their underestimations in Experiment 1, the *K* patients' overproductions in Experiment 3 at the longer intervals may reflect the effects of amnesia in that they forget time intervals that exceed the temporal parameters of working memory.

In contrast to *K* patients, *F* patients' proportional production scores, as a group, were not impaired in production, even at short intervals. But the normal-looking group means were an artifact of the extreme interindividual variance. The results were hard to interpret in view of the extreme interparticipant variability and notably the substantial overproduction by two participants, which counteracted the expected underproduction by the rest of the group in the group data. Fluctuations in attention may have been responsible for the variability in participants' performance.

Table 3. Correlations between estimated time (Experiment 1) and produced time (Experiment 3) for each interval

	All participants ($N = 32$)		Frontal ($N = 8$)		Korsakoff ($N = 8$)	
Time interval	*r*	*p*	*r*	*p*	*r*	*p*
10 s	−.31	.06	−.65	.05	.22	n.s.
30 s	−.52	.001	−.68	.05	−.01	n.s.
60 s	−.29	.09	−.50	n.s.	.14	n.s.
90 s	−.31	.05	−.45	n.s.	−.03	n.s.
120 s	−.31	.05	−.47	n.s.	.09	n.s.

Note. n.s.: nonsignificant.

GENERAL DISCUSSION

The relationship between episodic memory and time estimation was examined in *K* patients. The present study provides further evidence that amnesics are prone to impaired temporal duration judgments. *K* patients were impaired in both verbal estimation and time production for intervals beyond 30 s despite their intact subjective tempo for time passing. More specifically, they consistently showed curtailed verbal estimation while their temporal production was bidirectionally impaired. Underestimation and overproduction would be expected in patients who forget events that exceed working memory capacities. The correlations between time estimation and delayed memory measures in *K* patients were not significant, perhaps because of the floor effect of the amnesics' performance on delayed memory measures. It should be noted that there were trends in the predicted direction. Overall, data indicate that episodic memory is important in making accurate decisions regarding time intervals that exceed the limits of working memory.

Patients with frontal systems damage were also included in the study in order to examine the relative contributions of an internal biological clock, generic (nontemporal) cognitive estimation judgments, and working memory in decisions about passing time.

Previous studies have indicated that time estimation is dependent on an internal clock that is mediated by frontal brain regions (Church, 1984; Meck, 1983; Meck et al., 1984). Some researchers have reported that *F* patients' internal clocks are driven more quickly than the internal clocks of normal individuals (Carlson & Feinberg, 1968; Hoagland, 1933). In this study *F* patients overestimated time intervals, particularly at short durations. While the accelerated counting of some *F* patients may partially explain their propensity towards verbal overestimation, many of the *F* patients in this study did not demonstrate severe rapid counting. Nor was there consistency in the magnitude or direction (i.e., under- or overestimation) of their estimations over different time intervals. Consequently, problems with an internal clock mechanism do not wholly explain the data.

F patients' difficulties in time estimation could represent a generic problem in making decisions about abstract types of information. It is known that *F* patients often have difficulty on other types of cognitive estimation tasks such as estimating how much a familiar product is likely to cost (Smith & Milner, 1984) or inferring familiar facts from experience (e.g., "How tall is the average English woman's spine?"; Shallice & Evans, 1978). These types of decisions are different than those in the temporal tasks described above. Cognitive estimation decisions are referenced to experiences from the remote past and call for search and retrieval strategies of a type that *F* patients often find difficult. Estimates of time duration are made as soon as the test interval has ended, so that search and retrieval strategies are not called for. Also, whereas cognitive estimation errors by *F* patients are characterized by what appears to be random variance, the group mean estimates of duration offered by our *F* patients are systematically related to the actual duration of the interval in question. The relation of *F*s' estimate to actual time is roughly linear throughout the range of intervals that were tested.

In general, changes within awareness over time may provide a major source of temporal information (Fraisse, 1957). James (1890) referred to the extended present as "the lingerings of the past dropping successively away, and the incomings of the future making up the loss" (p. 606). These hypothetical lingerings and incomings may be identified as the flux of information in working memory. Fuster wrote of the role of working memory in "expanding the temporal perspectives of the system" (Fuster, 1985, p. 172). The working memory buffer is limited in its capacity, and as new information enters, old information must necessarily be expelled to make room for it. The more time has passed, the more likely it is that any given item in working memory has dropped out. The contents of working memory will turn over completely at a certain rate inversely related to the capacity of the store. Rather than being directly perceived, the subjective sense of time passing in the working memory time frame may be based on the rate at which its contents turn over and are completely renewed.

Prefrontal cortex is thought actively to maintain information in working memory (Cohen et al., 1997; Courtney et al., 1997), and frontal lesions interfere with working memory (Baddeley, 1986; Shimamura, 1995). Because new information continues to enter the store as before, old information must be expelled from it sooner than usual. The more rapid turnover of the information held in store will generate a sense of more time passing. This should be particularly striking at the shortest (10-s) interval, at which time rather little loss might be expected from a working memory that is intact. Our *F* patients overestimated that duration to a greater extent than any other time interval. Based on our data it is our belief that working memory plays a critical role in temporal duration judgment for short time intervals. The relationship between performance on the WCST and accuracy of time estimations was significant for brief periods of time (up to 30 s), within the time frame of working memory (Baddeley, 1986; Washburn & Astor, 1998; Wickelgren & Berian, 1971). For longer intervals, the tendency to overestimate appears to be counteracted and even reversed, depending upon the severity of the memory deficit.

In conclusion, this study examined a number of different hypotheses regarding time estimation. The question was addressed as to whether time estimations are based on a clock that can normally be read at the appropriate time but is either unavailable or systematically impaired in patient groups. If the internal clocks of *F* or *K* patients were abnormally accelerated, decelerated, or variable, time judgments would be correspondingly faulty but would still conform to a constant proportion of clock time. But in both *F* and *K* patients there was no such constancy. The estimates varied in their relation to clock time, depending on the amount of clock time involved. Therefore either the clock is inactivated and both patient groups are using alternative strategies or the hypothetical clock does not exist and the patients' deviations in time estimation reflects their memory-related difficulties. For *F* patients, these difficulties imply depleted working memory, which may inflate subjective estimation of very short intervals. For *K* patients, deficits in impaired episodic memory may account for curtailed estimation for longer durations (see Kinsbourne, in press, for a more detailed discussion).

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