Pergamon

PII: S0028–3932(97)00015–8

Neuropsychologia, Vol. 35, No. 6, pp. 747–758, 1997

Printed in Great Britain
0028–3932/97 $17.00+0.00

'Oops!': Performance correlates of everyday attentional failures in traumatic brain injured and normal subjects

IAN H. ROBERTSON,* TOM MANLY, JACKIE ANDRADE, BART T. BADDELEY and JENNY YIEND

MRC Applied Psychology Unit, Cambridge, U.K.

(*Received* 29 *September* 1996; *accepted* 24 *December* 1996)

Abstract—Insufficient attention to tasks can result in slips of action as automatic, unintended action sequences are triggered inappropriately. Such slips arise in part from deficits in sustained attention, which are particularly likely to happen following frontal lobe and white matter damage in traumatic brain injury (TBI). We present a reliable laboratory paradigm that elicits such slips of action and demonstrates high correlations between the severity of brain damage and relative-reported everyday attention failures in a group of 34 TBI patients. We also demonstrate significant correlations between self- and informant-reported everyday attentional failures and performance on this paradigm in a group of 75 normal controls. The paradigm (the Sustained Attention to Response Task—SART) involves the withholding of key presses to rare (one in nine) targets. Performance on the SART correlates significantly with performance on tests of sustained attention, but not other types of attention, supporting the view that this is indeed a measure of sustained attention. We also show that errors (false presses) on the SART can be predicted by a significant shortening of reaction times in the immediately preceding responses, supporting the view that these errors are a result of 'drift' of controlled processing into automatic responding consequent on impaired sustained attention to task. We also report a highly significant correlation of −0.58 between SART performance and Glasgow Coma Scale Scores in the TBI group. © 1997 Elsevier Science Ltd.

Key Words: attention; traumatic brain injury; attentional failures in daily life; sustained attention; brain damage.

Introduction

Oops!—Pouring cream into a requested black coffee or throwing away the vegetables while keeping their peelings are examples of action slips common in the everyday lives of normal people [3, 21]. Such slips tend to happen when attention to task is degraded through such factors as boredom, worry or dividing attention between several tasks simultaneously. There is a considerable normal variation in action-error-proneness [3], and brain damage—particularly to the frontal lobes of the brain—increases the likelihood that individuals will stray from intended goals and hence make errors [33, 34].

While many different cognitive processes may underlie such slips of action [32], it is likely that the sustained attention system of the brain described by Posner and Peterson [24] (1990) is important in such errors. In the present paper, we define sustained attention as the ability to self-sustain mindful, conscious processing of stimuli whose repetitive, non-arousing qualities would otherwise lead to habituation and distraction to other stimuli. In short, we distinguish between the capacity for endogenous modulation of alertness (self-sustained attention) with exogenously controlled alertness, which is governed by factors such as novelty, salience and stimulus change.

A possible link between slips of action on the one hand and sustained attention abilities on the other would be important for two reasons:

1. The search for attentional performance measures that correlate with everyday slips of action in the normal population have yielded little success [25], and this may be because adequate measures of sustained attention were not obtained.
2. We lack an adequate characterization of the attention deficits shown by traumatically brain injured (TBI) patients. The clinical tests that have been shown to be

* Address for correspondence: Ian H. Robertson, MRC Applied Psychology Unit, Rehabilitation Research Group, Box 58, Addenbrooke's Hospital, Cambridge CB2 2QQ, U.K.; tel.: +44 1223 355294, ext. 354; fax: +44 1223 516630; e-mail: ian.robertson@mrc-apu.cam.ac.uk.

sensitive to TBI, such as the Paced Auditory Serial Addition Test (PASAT) [11, 12], involve multiple cognitive operations, and hence it is not possible to delineate precisely the way in which patients fail on this test. In fact, most authors in this area interpret impaired clinical performance on such tests as being due to reduced speed of processing [11, 12, 42], rather than in terms of any more specific attentional processes. As shall be seen below, there are strong grounds for believing that sustained attention may be particularly compromised following TBI, and hence an attempt at a more theoretically coherent characterization of attentional failures following TBI, partly in terms of impaired sustained attention, seems warranted.

Traumatic brain injury particularly affects the frontal lobes [38, 43] and white matter [14, 38] of the brain. White matter damage has been shown to affect sustained attention particularly [26, 30], as have frontal lobe lesions mainly of the right hemisphere [6, 7, 23, 29, 46]. Reported problems of attention and concentration occur in the majority of severely traumatically brain-injured patients [17, 40].

In the present paper, we argue that the action slips of the normal population show characteristics in common with the attentional failures of traumatically brain injured patients, albeit in a less extreme form. We argue that one significant factor determining such slips are transient lapses in attention to task indicative of faulty sustained attention. In contrast to early work suggesting that sustained attention or vigilance in normal humans only shows decrements after several tens of minutes [16], recent research shows that right fronto-parietal systems are active over periods as short as 40 sec [23], and perhaps even over briefer periods [44].

The vulnerability of frontal and white matter areas to traumatic brain injury leads plausibly to the prediction that such patients will display sustained attention deficits, and such a prediction is also reinforced by the nature of the attention problems reported by relatives of traumatic brain injured patients. Detection of such deficits using conventional vigilance-based perceptual detection paradigms has yielded mixed results, however [4, 15, 22, 45], and some authors have even denied that traumatic brain injury results in attentional problems over and above difficulties presented by general mental slowing [42].

One reason for the difficulty experienced to date in finding consistent performance correlates of sustained attention deficits reported by brain injured people, may well lie in the sustained attention paradigms employed. Typically, continuous performance tests will require participants to monitor long sequences of stimuli and respond on detecting infrequent targets. Such paradigms are, arguably, highly vulnerable to rapid automatization in the sense of Schneider and Shiffrin's distinction between automatic and controlled, effortful processing [31]. Certainly, such tasks have problems with ceiling effects, which have led researchers to perceptually degrade targets or load working memory in order to reduce high levels of performance [22]. In support of this view, one study showed that vigilance decrements were only observed in a task that required controlled processing, but not in one where the responding relied on automatic processing [9].

We proposed that sustained attention to task would be taxed more heavily (and therefore that a greater range of performance would be seen in tasks of shorter duration) if the automatic response set could be transferred to the non-targets. In this case, when rare targets occur, active, controlled processing must be triggered to overcome or out-compete the prepotent automatic response. Hence, in the present study, we used a continuous performance paradigm involving key presses to frequently presented non-targets, but with the requirement to withhold motor responses to occasional targets (Sustained Attention to Response Task—SART). It was predicted that such a task would require a high level of continuous attention to response and be sensitive to transitory reduction in attention or 'lapses', while keeping to a minimum demands on other cognitive processes such as memory, planning and general intellectual effort.

Taking the view that action lapses in both normals and TBI patients can be attributed in part to sustained attention deficits, the following hypotheses were formulated.

Hypothesis 1

It was hypothesized that there would be a significant positive correlation in a non-brain damaged sample between sustained attention capacities (as measured by the SART error score) and self- and informant-reported attentional slips in everyday life.

It was further hypothesized that there would be no significant relationship between performance on a more conventional perceptual detection-based test of sustained attention (Triplets test) and these questionnaire measures, because of the proposed additional sensitivity of the SART to mild attentional deficits.

Hypothesis 2

We predicted that the TBI group would make significantly more errors than a matched control group on the SART sustained attention measure than on a conventional sustained attention detection-based paradigm.

Hypothesis 3

We predicted that, within the TBI group, pathology severity measured by Glasgow Coma Scale (GCS) scores and post-traumatic amnesia duration (PTA) would be strongly related to SART-assessed sustained attention performance.

Hypothesis 4

Traumatic brain injury and frontal lobe damage are often associated with impoverished awareness of the extent of problems [17, 37]. A number of factors may contribute towards this, including reduced sensitivity to feedback and reduced attention to errors [10]. It was therefore predicted that, whereas SART measures may show a relationship with self-reported attentional failures in a brain-injured group, the reports of informants who are familiar with the patient may show the strongest predictive relationship.

Hypothesis 5

Performance on the SART clearly requires the ability to withhold a response. Response inhibition in classic go/no-go paradigms has been shown to be impaired particularly after medial frontal lesions [13], and given the likely location of damage in traumatic brain injury, such a task is liable to be sensitive to subtle effects of damage. However, we have argued that this continuous performance task will be sensitive to the ability to endogenously sustain attention. Arbitrating between the relative contributions of an inefficiency in response inhibition *per se* and a failure to inhibit responses due to a lack of continuous attention to response is, of course, difficult and indeed somewhat circular within this task. However, assuming that these phenomena are separable and that both may contribute to a poor performance, it is possible to draw support for the claim that SART is sensitive to sustained attention by predicting:

1. The SART measures would show a stronger relationship to other validated measures of sustained attention (which have no such obvious response inhibition characteristics) than to measures of other attentional capacities (including one with an arguably strong response inhibitory component).
2. The occurrence of errors in the task can be predicted by monitoring fluctuations in the timing of accurate performance. In other words, an error can be seen not simply as an isolated failure in withholding a response but as the consequence of a failure in maintaining an optimum approach to the task over time. The SART stimuli are highly predictable and rhythmic, which allows the frequent responses to non-targets to become automatic and attentionally undemanding. Effective sustained attention to the task would act to counter this effect so that the response to an infrequent stimulus could be withheld. We would propose, therefore, that an absence of such attention would be revealed in a speeding of responses to stimuli, suggestive of the response being triggered by the anticipation of the stimuli rather than as a result of an evaluation of its relevance to response.

Experiment 1

Relationship between SART measures and everyday attentional lapses and other 'cognitive failures' among normal controls

The purpose of this study was to test the hypothesis that SART performance would correlate with everyday attentional failures in a normal population.

Method

Subjects. A group of 75 control subjects (23 male, 52 female), ranging in age from 18 to 65 (mean 34.0; S.D. 11.0), were recruited from the MRC Applied Psychology Unit Subject Panel.

Procedure. Subjects were assessed in a 1-hr session.

Apparatus and materials. The following tests were given:

Sustained attention to response test (SART)

Reliability was tested by administering the procedure to a sub-group of 25 normal subjects [15 women and 10 men, mean age 36.0 (S.D. 8.0); mean SART errors 4.56 (S.D. 4.88)] on two occasions over a period of 1 week. The Pearson correlation in the error score (false presses) between these two occasions was 0.76, showing that performance on this test is stable over time.

In the SART procedure, 225 single digits (25 of each of the nine digits) were presented visually over a 4.3-min period. Each digit was presented for 250 msec, followed by a 900-msec mask. Subjects responded with a key press to each digit, except 25 occasions when the digit 3 appeared, when they had to withhold a response. Subjects used their preferred hand. The target digit was distributed throughout the 225 trials in a pre-fixed quasi-random fashion. The period from digit onset to digit onset was 1150 msec. Subjects were asked to give equal importance to accuracy and speed in doing the task.

The digits were presented in one of five randomly allocated font sizes to enhance the demands for processing the numerical value, rather than simply setting a search template for some peripheral feature of the no-response target. These font sizes were 48 point, 72 point, 94 point, 100 point and 120 point, respectively (Symbol font), corresponding to a height varying between 12 mm and 29 mm.

The mask following each digit consisted of a ring with a diagonal cross in the middle. The total diameter of the circular mask was 29 mm. Both digits and mask were presented centrally in white against a black background of the computer screen. The screen (215 mm × 135 mm: Macintosh 170 PowerBook) was approximately 40 cm from the subjects' eyes, although no restrictions were placed on the subjects' movements.

Each session was preceded by a practice period consisting of 18 presentations of digits, two of which were targets.

Triplets test

One other experimental procedure was included for the purposes of the present study. This was a more conventional continuous-performance-type test, similar in form to the SART, but requiring a response to infrequent targets rather than a response to frequent non-targets and no response to a target. Two hundred and twenty-five digits were visually presented at an identical pacing to that used in the SART described above. In the Triplets test, however, subjects had to respond whenever they detected consecutive upward or downward runs of three digits—for example, 5, 6, 7 or 4, 3, 2. They responded to these stimuli with a mouse key press. As in the SART, there were 25 targets, and the duration of the task was also 4.3 min.

National adult reading test [20]

This reading test of irregularly spelled words gives an estimate of intelligence.

Questionnaire measures of attentional failures in everyday life

Cognitive failures questionnaire [3]. This self-report questionnaire measures slips of action and of memory in everyday life.

Cognitive failures questionnaire for others [3]. This questionnaire is given to relatives or friends of the subject on which they rate slips of action and of memory in everyday life.

Results

Hypothesis 1. It was hypothesized that there would be a significant positive correlation in normals between SART errors and reports (by both self and independent informants) of attentional and other cognitive errors in everyday life. There should be no such correlation between a conventional measure of sustained attention—the Triplets Test—and these questionnaire measures.

Table 1 shows a correlation matrix showing the interrelationships of the above measures, as well as their associations with age and intelligence. Only 60 out of the 75 subjects completed CFQ questionnaires, whereas 58 out of 60 supplied informant questionnaires.

Table 1 shows that, in the normal sample, the SART measures were not sensitive to the effects of age or of differences in estimated intelligence. There were significant correlations between the SART and both self- and informant-reported cognitive failures as measured by the CFQ questionnaires for self and informants. There were no significant correlations between the Triplets Test and the CFQ measures.

Hypothesis 1 was therefore supported for the SART, in that performance on the SART predicted self- and informant-reports of everyday attentional failures on the CFQ. The results also indicate that the attempt to create a measure that was sensitive to these forms of problem but not to general intellectual level was, at least for this sample, successful.

Experiment 2

Relationship between everyday attention failures, SART performance and brain damage severity among people with traumatic brain injury

The aims of this experiment were to test hypotheses 2–5 as outlined above. Each hypothesis is summarized below prior to each analysis.

Method

Subjects. A consecutive sample of 34 traumatically brain injured patients who were between 9 and 18 months

Table 1. Relationship between SART and Triplets performance and questionnaire self- and informant reports of attentional failures in a group of normals ($n=60$)

	CFQ self	CFQ relative	NART IQ	Age	Triplets (number correct)
SART	−0.27*	−0.29*	n.s.	n.s.	0.32*
Triplets (number correct)	n.s.	n.s.	n.s.	n.s.	
NART IQ	n.s.	n.s.		n.s.	n.s.
Age	n.s.	n.s.			

*$P<0.05$.
CFQ self: Cognitive Failures Questionnaire [3].
CFQ relative: Cognitive Failures Questionnaire for others [3].
NART: National Adult Reading Test.

post-injury and who had been admitted for at least 48 hr to Addenbrooke's hospital in Cambridge were assessed. The following exclusions were made:

1. Resident outside of the East Anglia area.
2. Pre-trauma history of epilepsy or other neurological condition.
3. History of drug or alcohol problems.
4. History of major psychiatric disorder.
5. Reported hearing difficulties.

The mean age of the sample was 34.8 (S.D. 13.4), with 24 males and 10 females. The mean lowest Glasgow Coma Scale (available for only 30 subjects) was 11.1 (S.D. 4.1). Post-traumatic amnesia duration (available for 32 subjects) was used to classify subjects into the severity categories 1—mild (less than one hour), 2—moderate (1–24 hr), 3—severe (1–7 days), 4—very severe (7 –28 days) and extremely severe (more than 28 days). By this classification, there were five mild, six moderate, five severe, five very severe and 11 extremely severe cases, respectively. The mean PASAT score (2-sec pacing) was 32.6 (S.D. 11.7), and the mean number of categories obtained on the Modified Wisconsin Card Sorting Test (maximum 6) [19] was 5.2 (S.D. 1.5). They showed a mean total error score of 7.7 (S.D. 7.9) on this latter test, of which a mean of 17.2% (S.D. 19.9) were perseverative. On the Stroop Test, they showed a mean decrease in speed for the conflict over the control condition of 17.4 sec (S.D. 7.3).

Procedure. Patients were assessed over two 2-hr sessions, having given informed consent to participating in the study.

Apparatus. All the measures, with the exception of the National Adult Reading Test, given to the controls in Experiment 1 were also given to the subjects in the current study. In addition, the following tests were given:

SART (see Experiment 1 above)

Tests of sustained attention.
Lottery subtest of the Test of Everyday Attention (TEA) [27, 28].
Telephone Search with Counting Subtest of the TEA.
Tests of attentional switching.
Modified Wisconsin Card Sorting Test [19].
Visual Elevator Subtest of the TEA.
Tests of selective attention.
Stroop Test [39].
Telephone Search Test of the TEA.

In addition to the above test procedures, the following were included:

Paced auditory serial addition test [11, 12] (2-*sec pacing*)

This test was included as it is one of the best established measures of attentional deficit following traumatic brain injury, and one aim of the study was to compare the sensitivity to traumatic brain injury of this test to the response inhibition procedures.

Triplets

One other experimental procedure was included for the purposes of the present study. This was a more conventional continuous-performance-type test, similar in form to the SART, but requiring a response to infrequent targets rather than a response to frequent non-targets and no response to a target. Two hundred and twenty-five digits were visually presented at an identical pacing to that used in the SART described above. In the Triplets test, however, subjects had to respond whenever they detected consecutive upward or downward runs of three digits—for example 5, 6, 7 or 4, 3, 2. They responded to these stimuli with a mouse key press. As in the SART, there were 25 targets, and the duration of the task was also 4.3 min.

Measures of everyday attention failures

The patient group and their relatives were also administered the same two rating scales (CFQ and CFQ for others) used with the normal group in Experiment 1 above. A total of 21 of the patients and relatives completed these instruments.

Comparison group for the brain injured subjects

Because the total sample of controls described in Experiment 1 above was not well matched in age, sex and verbal intelligence with the brain injured sample, for the purposes of testing Hypothesis 2, a subset of both groups was selected so as to be matched on these variables. The normal control group consisted of 17 subjects (six female, 11 male; mean age 39.8; S.D. 11.9; mean percentile IQ 81.7; S.D. 20.3) matched to a subsample of 22 of the patient group (six female, 16 male; mean age 34.2; S.D. 12.1; mean percentile IQ 77.6; S.D. 18.4) for age, sex and estimated premorbid IQ. The groups were compared on the response inhibition and other measures. Premorbid intelligence was assessed either by the National Adult Reading Test [20] or by the Spot-the-Word Test [1]. Percentile scores for estimated premorbid IQ were obtained, and a patient subgroup was selected who matched the control group on this as well as sex and age variables. Matching was successful as there were no statistically significant differences between the two groups on age, sex-ratio or IQ.

Table 2. Scores on SART and Triplets errors as well as SART reaction times, for the patient and control groups errors respectively

	SART errors	Triplets omissions	SART reaction time for the four presses prior to correctly withheld respones	SART reaction time for the four presses prior to non-withheld respones
Patients	7.6 (4.8)	3.9 (3.1)	372.8 (78.3)	300.4 (43.6)
Controls	4.0 (3.2)	5.0 (4.3)	397.1 (84.9)	305.9 (24.2)
F	7.0	2.7	0.71	0.14
P	0.01	n.s.	n.s.	n.s.

Results

Hypothesis 2: Do the SART measures distinguish controls from brain injured subjects? Table 2 shows the scores on the SART and Triplets errors.

Table 2 shows that the SART significantly discriminated between the two groups, but the Triplets task did not, as was predicted in the introduction. In fact, the control group made slightly fewer errors on the Triplets task than did the patients.

Hypothesis 3: Pathology severity measured by Glasgow Coma Scale (*GCS*) *scores and post-traumatic amnesia duration* (*PTA*) *will be strongly related to SART-assessed sustained attention performance*. For the purposes of testing this hypothesis, the whole group of 34 brain injured patients was included in the analysis. The correlations between Glasgow Coma Scale scores (GCS) and post-traumatic amnesia duration on the one hand, and attentional measures on the other, were calculated. Figure 1 summarizes the significant results. GCS scores were available for only 30 subjects.

Figure 1 shows that the SART and PASAT scores were the best predictors of GCS scores among the tests administered. PTA grade was best predicted by PASAT and Triplets. No other correlations were statistically significant at the 5% level.

The hypothesis that SART measures would predict the severity of an injury is supported, although the apparent complexity of the relationships between different cognitive tests and different estimates of severity requires further consideration.

The relative contributions of PASAT and SART to

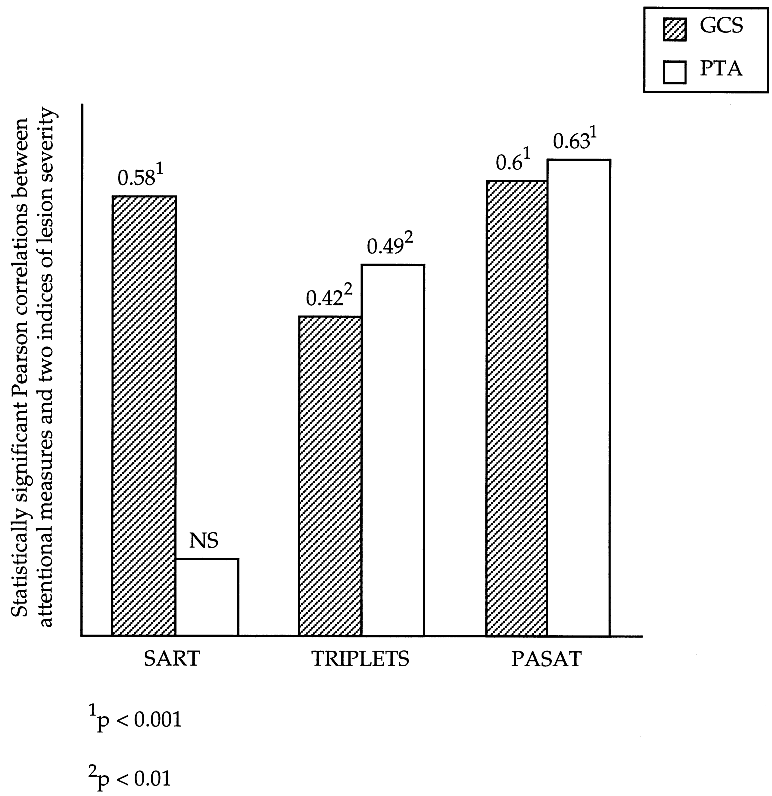

Fig. 1. Statistically significant correlations between key attentional measures on the one hand, and Glasgow Coma Scale scores and Post Traumatic Amnesia durations, respectively.

Table 3. Correlations between self-reports of attentional failures and test performance ($n=21$) ($*P<0.05$; $\dagger P<0.01$)

	SELF Cognitive failures (CQF)	INFORMANT Cognitive Failures (CQF)
Tests of attentional switching		
Wisconsin categories	n.s.	n.s.
Visual elevator	n.s.	−0.49*
Selective attention tests		
Stroop	n.s.	0.47*
Telephone search (TEA)	n.s.	n.s.
Sustained attention tests		
Telephone search with counting (TEA)	n.s.	n.s.
Lottery (TEA)	n.s.	n.s.
SART		
SART error	n.s.	0.44*
Other tests		
PASAT	n.s.	−0.73†
Triplets	n.s.	n.s.
GCS (Glasgow Coma Scale)	n.s.	−0.51*
PTA (post-traumatic amnesia duration)	n.s.	0.58†

$*P < 0.05$.
$\dagger P < 0.01$.

predicting GCS were therefore assessed using multiple regression. PASAT and SART were entered as independent variables. Only SART showed any significant independent effect in the regression ($t=-2.03$; $P=0.05$). This was confirmed by the fact that, whereas the SART accounts for 33.7% of the variance in GCS on its own, adding in PASAT as an independent variable added only a negligible 3% to the explained variance.

Hypothesis 4: Attentional test correlations rating scale measures of everyday problems of attention for brain injured people. Self ratings. The relationship between self- and informant-ratings of attentional failures on the CFQ scales was examined. Table 3 shows the correlations between self-reports and informant-reports of attentional failures and test performance. Rating scale data were available on only 21 of the brain injured subjects.

Table 3 shows that zero out of 11 correlations between self-reports of attentional failures and attentional test performance are statistically significant, in contrast to six out of 11 (54%) of informant-reports of attentional failures and test performance shown in Table 3.

Given the relatively low number of brain injured people on whom self and informant reports were available (21), some caution is needed in drawing firm conclusions from the correlational data. However, the results are certainly consistent with the proposal that, due to problems with insight and attention, informants' reports would be more sensitive to cognitive problems experienced by the brain-injured people than self-reports.

Hypothesis 5. (a) Relationship of SART with other tests of attention. We argued that SART is, to a great extent, a test of sustained attention, and hence we predict a much stronger relationship between SART and tests of sustained attention than with other attentional tasks, and in particular with tests where response inhibition is important, such as the Wisconsin Card Sorting Test, the Visual Elevator Subtest of the Test of Everyday Attention and Stroop.

To test this hypothesis, we carried out three stepwise muliple regression analyses, with SART as the dependent variable in each case. Table 4 shows these three regressions. In each case, one of the three tests, presumed to be sensitive to response inhibition, was entered into the regression first, and then two tests of sustained attention (Lottery and Telephone Search with Counting Subtests of the Test of Everyday Attention) were each loaded in turn into the regression to determine how much extra variance, if any, would be explained.

In addition, in each regression, we also loaded in PASAT as the final independent variable, in order to determine whether this sensitive yet complex benchmark test of TBI attention deficits would add significantly to the explained variance in SART.

The first regression in Table 4 shows that Wisconsin perseverative errors are non-significantly correlated with SART. The addition of the Lottery added almost 18% of variance explained, whereas the addition of Telephone Search with Counting (TSC) added a further 12%, giving a total explained variance of 30%. Adding PASAT, however, contributed a non-significant extra 2% to the SART explained variance.

The second regression in Table 4 showed near identical results, with the Visual Elevator (VE) test showing no significant relationship with SART; yet the addition of two sustained attention tasks produced an explained variance of 32%. Again the PASAT did not significantly improve on this.

The third regression produced similar results with

Table 4. Multiple regressions of attentional measures on SART

		SART		Percentage variance explained	Additional variance	P of added variable
		R	R^2			
A. Wisconsin	1. WISC	0.06	0.003	0.3	—	n.s.
	2. WISC + Lottery	0.42	0.18	18	17.7	<0.03
	3. WISC + Lotter + TSC	0.55	0.30	30	12	<0.05
	4. WISC + Lotter + TSC + PASAT	0.57	0.32	32	2	n.s.
B. Visual elevator	1. Visual elevator	0.13	0.02	2	—	n.s.
	2. VE + Lottery	0.42	0.18	18	16	<0.03
	3. VE + Lottery + TSC	0.57	0.32	32	16	<0.03
	4. VE + Lottery + TSC + PASAT	0.60	0.36	36	4	n.s.
C. Stroop	1. Stroop (Increase in time of conflict over no-conflict condition)	0.14	0.02	2	—	n.s.
	2. Stroop + Lottery	0.40	0.16	16	14	<0.06
	3. Stroop + Lottery + TSC	0.52	0.27	27	11	<0.06
	4. Stroop + Lottery + TSC + PASAT	0.54	0.29	29	2	n.s.

Stroop, which, like Wisconsin and VE, did not correlate significantly with SART. Again, the explained variance only became significant when sustained attention tasks were added, and again the PASAT added no significant extra variance.

There were no statistically significant correlations with any of the other attentional tests with the exception of Triplets—another measure of sustained attention—which correlated at a marginally significant level, 0.34 ($P<0.06$) with SART. The hypothesis that SART is sensitive to sustained attention and not simply to impaired ability to inhibit a response *per se* is therefore supported.

Predicting errors in SART on the basis of the timing of accurate responses

In order to test whether an error on the SART (responding to a target) could be predicted on the basis of performance characteristics, which may reflect a lessening of attention to the task, we carried out the following analysis. Reaction times for each set of four correct presses prior to correctly inhibited targets (i.e. presentations of the number 3, which did not result in a response) were compared with each set of four correct presses prior to a mistakenly pressed target (i.e. presentations of the number 3, which did result in a response) in the patient group. The mean reaction time prior to correctly given responses was 380.6 (S.D. 64.4), whereas the mean reaction time in the trials prior to mistaken presses was 345.1 (S.D. 59.5). This was a statistically significant difference ($t=-3.325$; $P<0.01$).

A similar finding was obtained for the controls. The mean pre-correct-trial RT for controls was 376.9 (S.D. 54.7), whereas the pre-false-press mean RT was 328.1 (S.D. 53.5). This difference remained statistically significant ($t=-3.65$; $P<0.025$) after correction of significance level for multiple t-tests. For both groups then, errors may be predicted by a reduction in RTs, interpreted in this task, where the occurrence of stimuli is highly predictable, as indicating a lessening of active attention.

There is also some indication of a group difference on the effect of an error on response characteristics. The control group showed a significant increase in RT between the four trials leading up to an error and the four trials following an error [mean RT prior to error; 328.112 (S.D. 53.4), mean RT following error 362.782 (S.D. 84.3), $t=-2.157$, $P<0.05$], suggesting clear effects on response style. The patients tended not to show or maintain such error effects on response style [mean RT prior to error; 345.1 (S.D. 59.5), mean RT following error 348.9 (S.D. 78.1), $t=-0.36$; n.s.].

Figure 2 shows graphically the mean reaction times for the four responses preceding, and the four responses after, correct and error trials, respectively. Figure 2 shows these data for, respectively, the control group, for the TBI group whose error rate was less than 1 standard deviation from the control group's mean errors and for the TBI group, who made in excess of two standard deviations from the control group's errors.

A disproportionate variability in RTs, measured by within-subject variability, has been noted in TBI patients, interpreted as indicating a deficit in sustaining consistent performance [38]. In the present study, analysis of variance revealed a statistically significant effect of group on RTs ($F=22.59$, $P<0.0001$), with the TBI subjects showing a greater variability (mean standard deviation = 99.3, S.D. 44.8) than the control group (mean standard deviation = 67.9, S.D. 19.3).

Discussion

All five hypotheses received support from the data. To summarize:

1. In normal controls, SART performance significantly

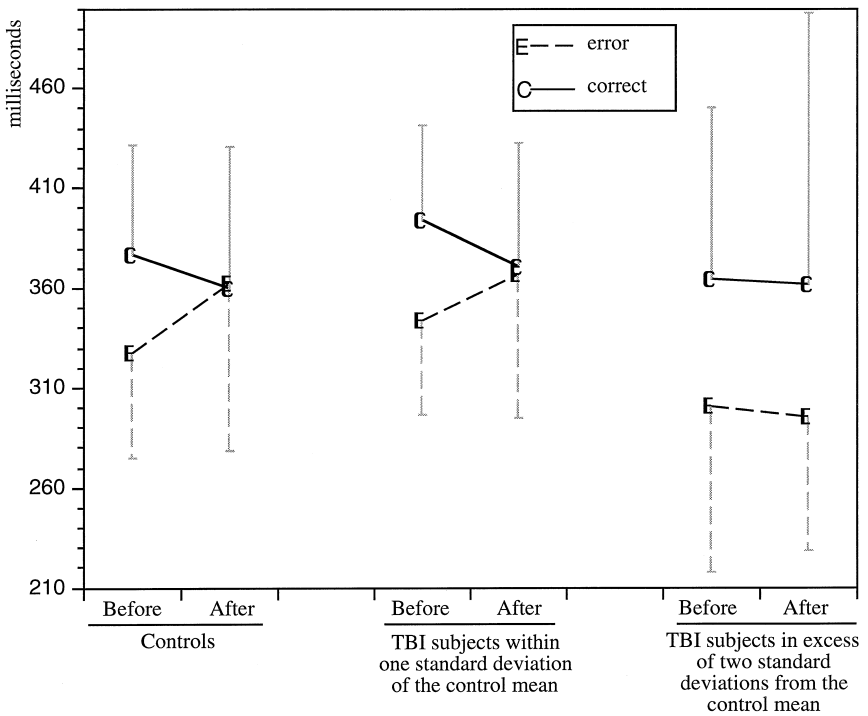

Fig. 2. SART: Mean RTs for the four trials preceding and following correct or incorrect responses to target presentations for three groups.

correlated with self-reports of attentional and other 'cognitive failures' in everyday life, as well as with informant reports of such failures.

2. SART performance discriminated an unselected sample of brain injured subjects from age-, sex- and IQ-matched controls, whereas a more conventional perceptually-based vigilance task (Triplets) did not.
3. SART forms, along with the PASAT, the best predictor of severity of brain damage as measured by lowest Glasgow Coma Scale scores of all the cognitive measures administered. Coma severity was the principal determinant of poor SART performance.
4. SART, along with several other attentional measures, was strongly correlated with informant reports of daily life attentional failures in the TBI group. No attentional measures were correlated with self-reported problems with attention in this group.
5. Variance in SART performance was predicted by sustained attention test performance and not by performance on tests presumed to be sensitive to response inhibition. Errors on the SART measure were predicted from participants' performance on correct non-target items preceding the occurrence of a target: subjects show significant speeding up of responding prior to error responses. TBI patients also show a significantly reduced tendency to slow down responding after an error compared to the controls. TBI patients showed a significantly greater variability in RTs to stimuli compared to controls. As no significant time-on-task effects emerged for either group in terms of errors or RTs, this finding suggests that local fluctuations in attention or 'lapses' may provide a better account of poor performance on this task than a simple decrement over time. These results support the hypothesis that difficulty in maintaining continuous attention to the task provides a more satisfactory account for failure than a simple difficulty in inhibiting responses.

The hypotheses set out in the introduction were therefore broadly supported. The SART appears to be sensitive to sustained attention deficits and predicts self-reported and informant-reported attentional failures in normals, and informant-reported attentional failures in brain injured participants. Performance on the SART measures significantly discriminated an unselected sample of brain injured patients (with a wide variety of severity and post-injury symptoms) from normal age- and premorbid IQ-matched controls. SART measures were as effective as the PASAT in predicting some measures of severity of injury.

The fact that Triplets did not discriminate between the TBI patients and normal controls, whereas the SART did, may be due to the greater sensitivity and lower automatizability of the SART, as argued in the introduction. Though the Triplets is not as simple as some vigilance tasks where only single stimuli have to be detected, we argue that numerical sequences such as 3, 4, 5 are sufficiently familiar that their detection does indeed require less sustained attention to task than the requirement to inhibit a response in SART. We do, however, acknowledge the possibility that this finding may be due to the response inhibition aspects of the SART, although the fact that SART correlates uniquely with sustained attention and not other measures lends support to the former argument.

As a relatively unselected group of TBI subjects of mixed severity, the fact that they were broadly within normal limits on conventional measures, such as Wisconsin, is perhaps not surprising. As a group of above-average IQ, this fact may have served to obscure executive deficits. Attentional and frontal deficits can only be detected with difficulty with sophisticated experimental methods in some studies with unselected populations [41, 42], and the relative insensitivity of these measures for such populations may explain, in part, the superior performance of SART in the present study.

The finding that observed (by a close informant) attentional slips in everyday life can be predicted by laboratory test performance is the first such finding in the literature, to our knowledge. This result suggests a normal continuum of sustained attention capacity, bearing strongly on everyday life performance. This allows us to consider the problems shown by TBI subjects in a similar light to those shown by a proportion of the normal population. The results also emphasize the need, in brain injured groups, to consider the reports of informants who know the patient well and not simply to rely on self-reports in considering cognitive difficulties.

The SART measures, while being sensitive to variations in attentional performance within brain injured and normal populations, also act as a powerful discriminator of group. This finding suggests that the measures may be a useful addition in clinical assessment, in both predicting real life difficulties and in supporting victim and family claims that an injury has led to impairment and disability.

Other results also support the use of such measures in this capacity. Currently, the PASAT is the key instrument that is sensitive to the sometimes subtle processing impairments, which can result from traumatic brain injury. However, as discussed, this sensitivity must be somewhat set against the difficulty in interpreting performance due to the significant contributions of arithmetical ability, age and general intellectual resources [2, 5, 8], not to mention the rather intimidating qualities of the task. At least in the samples tested, the SART was resistant to differences in age and estimates of IQ. Conceptually, it is an easy task to pick up, it has little in the way of a memory load (there is only one target to keep in mind) and it only requires identification of single digits. It seems likely that another benefit of the simplicity of the SART will be its amenability to fine-grained analysis through the manipulation of its few parameters.

Whereas the SART appears to be as strong a predictor of some aspects of injury severity as PASAT, SART was associated only with coma severity, but not with post-traumatic amnesia duration, whereas PASAT was associated with both. In considering these relationships, it is of note that coma severity, as assessed by GCS, is associated with white matter damage [47], which, in turn, has been associated with sustained attention deficits [38]. The particular demands that the SART makes on the ability to sustain attention to response therefore may underlie this association. PASAT is arguably a more complex task demanding greater cortical involvement and hence may be less strongly linked to white matter damage and less specifically related to coma severity.

Whereas it has been proposed that the SART is sensitive to variation in the ability to endogenously sustain attention to task, as outlined in the introduction, a strong counter claim is that the test is sensitive to the ability to inhibit a response, a known impairment following frontal lesions, and that additional accounts are redundant. Indeed, impairments of the response selection stage of information processing following closed head injury have been reported in several Australian studies [18, 35, 36].

Simply suggesting that difficulties in inhibiting a response, whether in cognitive tests or in real life, are the result of an absence of sustained attention to task moves this no further. One way of delineating the relative contributions to performance would be to consider further the effects of time on task. This has been the traditional method in the search for sustained attention deficits in this group [45].

For reasons of producing a clinically useful measure, the SART used in this study does not provide sufficient targets to perform this type of analysis reasonably in terms of error rates. Whereas this is amenable to further experimental investigation, it is not clear that such a view of an incremental decline over time is the best fit for the complaints of patients. Such a design would not, for example, be sensitive to a pattern of attentional fluctuation, of drifting off and on task, which may occur over periods of just a few seconds [23, 44].

Another route to disambiguating the factors underlying SART failure is to consider its relationship to other tests. It has been demonstrated that the SART shows stronger relationships with measures of sustained attention than with other types of attention. What we have been unable to demonstrate is that it sits better with tests of sustained attention than it does with a 'pure' measure of response inhibition. A problem with doing this, from our perspective, is that it is difficult to conceive of such measures that are not themselves vulnerable to a sustained attention to response argument or that are not contaminated with extraneous demands.

A third source of evidence, that we have suggested is of relevance to this question, is in considering the RTs to non-targets that precede and follow the occurrence of targets. It was proposed that, because of the task characteristics of simplicity, rhythmicity and predictability, that waning attention to response would be characterized by a speeding of RT to stimuli. Subjectively, setting up such a response pattern seems to be the least effortful and most errorful way of performing the task. Certainly errors were predictable by considering this factor alone. It has also been claimed that the return to longer RTs that follow errors, at least in normal participants, corresponds with a return of effortful sustained attention to the task.

The slowing of response times following errors also may arise because subjects adopt a more conservative response criterion, or because they inhibit automatic responses to a greater degree once an error has been made. Thus, on the basis of the reaction time (RT) evidence alone, one could not argue in favour of the sustained attention hypothesis. Taken together with the regression analysis data from Table 4, however, the sustained attention hypothesis explanation of the RT data becomes slightly stronger, although certainly not conclusive.

The convergence of evidence lends support to the view that the SART may be particularly sensitive to the ability to sustain attention to a dull but demanding task, but is insufficient to fully dismiss alternative accounts. An advantage of the test's sensitivity to variations in normal populations is that such questions can be further pursued in such groups.

In summary, we believe that we have developed a task that is sensitive to attentional deficits in traumatic brain injury patients and that also may be sensitive to individual differences in everyday attention failures in normal controls. The simplicity of the paradigm that shows such strong correlations with biological markers of severity of damage and everyday life performance means that considerable strides can be made in the future towards further delineating the nature of the deficits and ultimately providing adequate rehabilitation of these deficits.

References

1. Baddeley, A. D., Emslie, H. and Nimmo-Smith, I., *The Speed and Capacity of Language Processing Test*. Thames Valley Test Company, Bury St Edmunds, U.K., 1992.
2. Brittain, J. L., LaMarche, J. A., Reeder, K. P., Roth, D. L. and Boll, T. J. Effects of age and IQ on paced auditory serial addition task (PASAT) performance. *The Clinical Neuropsychologist* **5,** 163–175, 1991.
3. Broadbent, D. B., Cooper, P. F., FitzGerald, P. and Parkes, K. R. The Cognitive Failures Questionnaire (CFQ) and its correlates. *British Journal of Clinical Psychology* **21,** 1–16, 1982.
4. Brouwer, W. H. and Wolffelaar, P. C. V. Sustained attention and sustained effort after closed head injury: Detection and 0.10 Hz heart rate variability in a low event rate vigilance task. *Cortex* **21,** 111–119, 1985.
5. Chronicle, E. P. and MacGregor, N. A., Are PASAT scores related to mathematical ability? *Neuropsychological Rehabilitation*, in press.
6. Cohen, R. M., Semple, W. E., Gross, M., Holcomb, H. J., Dowling, S. and Nordahl, T. E. Functional localization of sustained attention. *Neuropsychiatry, Neuropsychology and Behavioural Neurology* **1,** 3–20, 1988.
7. Cohen, R. M., Semple, W. E., Gross, M., King, A. C. and Nordahl, T. E. Metabolic brain pattern of sustained auditory discrimination. *Experimental Brain Research* **92,** 165–172, 1992.
8. Deary, I. J., Langan, S. J., Hepburn, D. A. and Frier, B. M. Which abilities does the PASAT test? *Personality and Individual Differences* **12,** 983–987, 1991.
9. Fisk, A. D. and Schneider, W. Controlled and automatic processing during tasks requiring sustained attention: A new approach to vigilance. *Human Factors* **23,** 737–750, 1981.
10. Freedman, P. E., Bleiberg, J. and Freedland, K. Anticipatory behaviour deficits in closed head injury. *Journal of Neurology, Neurosurgery, and Psychiatry* **50,** 398–401, 1987.
11. Gronwall, D. M. A. and Wrightson, P. Delayed recovery of intellectual function after minor head injury. *Lancet*, **II** (7874), 1452, 1974.
12. Gronwall, D. M. A. and Wrightson, P. Cumulative effects of concussion. *Lancet* **11,** 995–997, 1975.
13. Leimkuhler, M. E. and Mesulam, M. M. Reversible go–no go deficits in a case of frontal lobe tumor. *Annals of Neurology* **18,** 617–619, 1985.
14. Levin, H. S., High, W. M., Williams, D. H., Eisenberg, H. M., Amparo, E. G., Guinto, F. C. and Ewert, J. Dichotic listening and manual performance in relation to magnetic resonance imaging after closed head injury. *Journal of Neurology, Neurosurgery, and Psychiatry* **52,** 1162–1169, 1989.
15. Loken, W. L., Thornton, A. E., Otto, R. L. and Long, C. L. Sustained attention after closed head injury. *Neuropsychology* **9,** 592–598, 1995.
16. Mackworth, F. J. Vigilance, arousal and habituation. *Psychological Review* **75,** 308–322, 1968.
17. McKinlay, W. M. The short-term outcome of severe blunt head injury as reported by relatives of the injured persons. *Journal of Neurology, Neurosurgery, and Psychiatry* **44,** 527–533, 1981.
18. Murray, R., Shum, D. K. and McFarland, K. Attentional deficits in head-injured children: An information-processing analysis. *Brain and Cognition* **18,** 99–115, 1992.
19. Nelson, H. A modified card sorting test sensitive to frontal lobe deficits. *Cortex* **12,** 313–324, 1976.
20. Nelson, H., *The National Adult Reading Test* (*NART*) *Test*. NFER, Windsor, 1982.
21. Norman, D. A. and Shallice, T., Attention to action: willed and automatic control of behaviour. In *Consciousness and Self Regulation*, Vol. 4, ed. R. J. Davidson, G. E. Schwartz and D. E. Shapiro. Plenum, New York, 1986, pp. 1–18.
22. Parasuraman, R., Mutter, S. A. and Molloy, R. Sustained attention following mild closed-head injury. *Journal of Clinical and Experimental Neuropsychology* **13,** 789–811, 1991.
23. Pardo, J. V., Fox, P. T. and Raichle, M. E. Localization of a human system for sustained attention by positron emission tomography. *Nature* **349,** 61–64, 1991.
24. Posner, M. I. and Peterson, S. E. The attention system of the human brain. *Annual Review of Neuroscience* **13,** 25–42, 1990.
25. Rabbitt, P. and Abson, V. 'Lost and Found': Some logical and methodological limitations of self-report

questionnaires as tools to study cognitive ageing. *British Journal of Psychology* **81,** 1–16, 1990.
26. Rao, S. M., Leo, G. J. and Haughton, V. M., Aubin-Faubert, P. S. and Bernardin, L. Correlation of magnetic resonance imaging with neuropsychological testing in multiple sclerosis. *Neurology* **39,** 161–166, 1989.
27. Robertson, I. H., Ward, A., Ridgeway, V. and Nimmo-Smith, I., *Test of Everyday Attention*. Thames Valley Test Company, Bury St Edmunds, U.K., 1994.
28. Robertson, I. H., Ward, T., Ridgeway, V. and Nimmo-Smith, I., The structure of normal human attention: The Test of Everyday Attention. *Journal of the International Neuropsychological Society* **2,** 525–534, 1996.
29. Rueckert, L. and Grafman, J. Sustained attention deficits in patients with right frontal lesions. *Neuropsychologia* **34,** 953–963, 1996.
30. Rueckert, L., Sorensen, L. and Levy, J. Callosal efficiency is related to sustained attention. *Neuropsychologia* **32,** 159–173, 1994.
31. Schneider, W. and Shiffrin, R. M. Controlled and automatic human information processing: 1. Detection, search and attention. *Psychological Review* **84,** 1–66, 1977.
32. Schwartz, M. F., Mayer, N. H., FitzpatrickDeSalme, E. J. and Montgomery, M. W. Cognitive theory and the study of everyday action disorders after brain damage. *Journal of Head Trauma Rehabilitation* **8,** 59–72, 1993.
33. Shallice, T. and Burgess, P. Deficit in strategy application following frontal lobe damage in man. *Brain* **114,** 727–741, 1991.
34. Shallice, T. and Burgess, P., Higher-order cognitive impairment and frontal lobe lesions in man. In *Frontal Lobe Function and Dysfunction*, ed. H. S. Levin, H. M. Eisenberg and A. L. Benton, Oxford University Press, New York, 1991, pp. 125–138.
35. Shum, D. H. K., McFarland, K. and Bain, J. D. Effects of closed head injury on attentional processes: Generality of Sternberg's additive factor method. *Journal of Clinical and Experimental Neuropsychology* **16,** 547–555, 1994.
36. Shum, D. H. K., McFarland, K., Bain, J. D. and Humphreys, M. S. Effects of closed head injury on attentional processes: An information processing stage analysis. *Journal of Clinical and Experimental Neuropsychology* **12,** 247–264, 1990.
37. Stuss, D. and Benson, D. F. Neuropsychological studies of the frontal lobes. *Psychological Bulletin* **95,** 3–28, 1983.
38. Stuss, D. and Gow, A. D. Frontal dysfunction after traumatic brain injury. *Neuropsychiatry, Neuropsychology and Behavior Neurology* **5,** 272–282, 1992.
39. Trenerry, M. R., Crosson, B., DeBoe, J. and Leber, W. R., *Stroop Neuropsychological Screening Test*. Psychological Assessment Resources, Odessa, FL, 1989.
40. VanZomeren, A. H. and Burg, W. V. D. Residual complaints of patients two years after severe closed head injury. *Journal of Neurology, Neurosurgery, and Psychiatry* **48,** 21–28, 1985.
41. VanZomeren, A. H. and Deelman, B. G. Differential effects of simple and choice reaction after closed head injury. *Clinical Neurology and Neurosurgery* **79,** 81–90, 1976.
42. VanZomeren, A. H. and Deelman, B. G. Long term recovery of visual reaction time after closed head injury. *Journal of Neurology, Neurosurgery, and Psychiatry* **48,** 21–28, 1978.
43. Varney, N. R., Bushnell, D. L., Nathan, M., Kahn, D., Roberts, R., Rezai, K., Walker, W. and Kirchner, P. NeuroSPECT correlates of disabling mild head injury: Preliminary findings. *Journal of Head Trauma Rehabilitation* **10,** 18–28, 1995.
44. Whitehead, R. Right hemisphere processing superiority during sustained visual attention. *Journal of Cognitive Neuroscience* **3,** 329–335, 1991.
45. Whyte, J., Polansky, M., Fleming, M., Coslett, H. B. and Cavallucci, C. Sustained arousal and attention after traumatic brain injury. *Neuropsychologia* **33,** 797–813, 1995.
46. Wilkins, A. J., Shallice, T. and McCarthy, R. Frontal lesions and sustained attention. *Neuropsychologia* **25,** 359–365, 1987.
47. Wilson, J. T. L., Hadley, D. M., Wiedmann, K. D. and Teasdale, G. M. Neuropsychological consequences of two patterns of brain damage shown by MRI in survivors of severe head injury. *Journal of Neurology, Neurosurgery, and Psychiatry* **59,** 328–331, 1995.