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RESEARCH ARTICLE

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Multitasking costs in close-head injury patients

A fine-grained analysis

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Abstract The issue of whether severe close-head injury (CHI) patients suffer from disproportionate dual-task deficits compared with matched controls was investigated in two experiments. In the first experiment, either one or three masked letters were presented at the center of a monitor, followed by a pure tone at variable stimulus-onset asynchronies (SOAs). In half of the blocks of trials, the task on the letters required a delayed report of the letters at the end of each trial; in the other half of the blocks, the letters had to be ignored. The tone task always required an immediate manual response based on the tone pitch. In the second experiment, either three masked letters or three masked digits were presented with equal probability in each trial, followed by a tone at variable SOAs. The task required the delayed report of the characters only if they were letters, or ignoring the characters if they were digits. In both experiments, CHI patients and matched controls both exhibited an SOA-locked slowing of the reaction time (RT) to the tone: When characters had to be encoded for delayed report, tone RT increased progressively as SOA was decreased. The SOA effect on tone RT was more pronounced for CHI patients than for controls, suggesting that a substantial component of the slower processing time for CHI patients was related to a selective increase at a central stage of processing shared by the two tasks. Implications for models of the CHI effects on human performance are discussed.

Keywords Closed-head injury · Visual encoding · Dual-task performance · Speed of processing

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Introduction

Mental slowness and poor concentration are terms often used by clinicians to describe the most frequent association of symptoms resulting from a severe closed-head injury (CHI; Brooks 1984). These definitions pertain to two measurable aspects of CHI patients' behavior when observed in a controlled environment. "Mental slowness" refers to the fact that CHI patients are consistently slower than uninjured subjects in carrying out a variety of isolated speeded tasks (Ferraro 1996; Ponsford and Kinsella 1992; Van Zomeren et al. 1984). "Poor concentration" refers to the fact that CHI patients seem to experience an exacerbated difficulty compared with uninjured subjects when more than one task must be performed close-to-concurrently, suggesting some form of limitation in focusing on more than one activity at the same time (Gronwall 1987; Ponsford and Kinsella 1991).

Although numerous studies on CHI effects have been reported over the past two decades, few investigators have considered the hypothesis that there may be a common cause underlying single-task slowness and multitasking difficulty. Rather, theorizing about the causes of these symptoms has tended to diverge. Accounts of single-task slowness have frequently been cast in terms of reduced speed at one or more stages of information processing (Schmitter-Edgecombe et al. 1992; Shum et al. 1990), whereas multitasking costs have almost invariably been associated with a control disorder, i.e., a problem in organizing and scheduling sets of mental operations shared by two or more tasks (Hartman et al. 1992; McDowell et al. 1997; Park et al. 1999).

It has become traditional to treat RT-slowing and multitasking costs as dissociable phenomena. One reason

for this is the fact that, despite the ubiquity of RT-slowing effects in experimental investigations on CHI, studies on multitasking performance have sometimes provided evidence of increased dual-task costs for CHI patients compared with uninjured subjects (Park et al. 1999; Stablum et al. 1994, 1996, 2000), whereas sometimes they have not (Brouwer et al. 1989; Gentilini et al. 1989; Hartman et al. 1992; Riese et al. 1999; Spikman et al. 1996; Veltman et al. 1996; Vilkki et al. 1996).

Umiltà and Stablum (1998) have recently argued that these inconsistent results may be due to the different sensitivity of the methodologies used to test CHI control deficits in these studies. As Umiltà and Stablum (1998) observed, studies reporting dual-task costs for CHI patients no greater than for controls have generally focused on errors in classical neuropsychological tests (Tower of London, PASAT) when administered in combination with simple, purportedly interfering, tasks (e.g., articulatory suppression or random-number generation; see Azouvi et al. 1996, for an example). Magnified CHI dual-task deficits are typically detected through the use of chronometric paradigms originating from studies on executive functions in normals (e.g., the task-switch paradigm; Rogers and Monsell 1995). According to Umiltà and Stablum (1998), chronometric tests would therefore provide a more effective tool to examine the behavioral effects produced by a head trauma as compared to classical neuropsychological testing. Extending this suggestion to the present case, one may also argue that the comparison of single-task versus dual-task costs in chronometric tasks constitutes the only avenue to disentangle whether the frequent association of RT slowing and disproportionate dual-task impairments in CHI patients arises from a common cause or functionally independent causes.

A recent attempt in this area has been made by Dell'Acqua et al. (2001) using a psychological refractory period (PRP; Welford 1952; see Pashler 1994, for a review) study. In each trial of the PRP paradigm employed by Dell'Acqua and colleagues (experiment 1), two bidimensional stimuli, a tone (T_1) varying in frequency and a circular pattern (T_2) varying in color, were presented sequentially at a stimulus onset asynchrony (SOA) of 350 ms, 900 ms, or 1,550 ms. Each stimulus was associated with a speeded, two-alternative choice reaction time, RT_1 and RT_2, respectively. RT_1 was the time taken to emit a vocal response based on the tone pitch (either high or low), and RT_2 was the time taken to emit a manual response based on the circle color (either red or blue). The stimuli were presented through different sensory modalities, and different motor effectors were used to respond to the stimuli. Thus, this PRP condition was designed to combine two simple tasks based on the discrimination of easily detectable physical features of the stimuli, while minimizing potential sources of cross-task, perceptual, and motor interference. The results indicated that both RT_1 and RT_2 produced by CHI patients in the present PRP paradigm were consistently longer than RT_1 and RT_2 produced by controls. Few errors were made by either group of participants in the two tasks, with accuracy being, on average, slightly higher for CHI patients than for controls. Both CHI patients and controls showed a classical PRP effect; i.e., SOA variations produced no effects on RT_1, but substantial effects on RT_2, in the expected form of a progressive RT_2 increase as SOA was decreased. A comparison of the size of the PRP effect (RT_2 at the shortest SOA–RT_2 at the longest SOA) shown by CHI patients and controls was quite informative: The PRP effect shown by CHI patients was increased by a quantity corresponding closely to the overall slowing effect shown by CHI patients on RT_1.

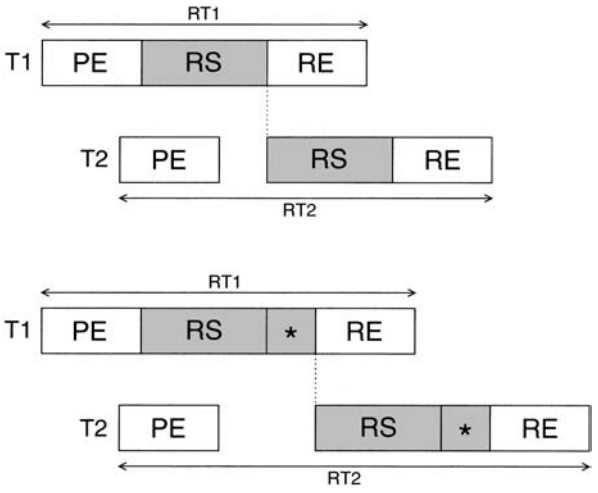

Fig. 1 Stage diagrams showing the interaction between mental operations in a psychological refractory period (PRP) paradigm (experiment 1; Dell'Acqua et al. 2001) in condition of high temporal overlap between tasks (i.e., at short stimulus-onset asynchronies, SOAs), for both control subjects (*upper two rows*) and close-head injury (CHI) patients (*lower two rows*). *PE* Perceptual encoding, *RS* response selection, *RE* response execution. RT_1 and RT_2 are estimates of the time taken to respond to T_1 and T_2, respectively. Postponement of RS_2 is caused by the forced seriality of central operations (because central mechanisms cannot carry out RS_1 and RS_2 in parallel). RS_2 can resume only after central mechanisms are no longer occupied with RS_1. This period of processing suspension for RS_2 is reflected in the prolongation of RT_2 at short SOAs compared with long SOAs, the PRP effect. Effects of CHI are hypothesized to be entirely reflected in the prolongation (*asterisks*) of the time taken to carry out central operations, such as RS. A longer period of processing suspension (hence, a more pronounced PRP effect) is expected for CHI patients than for controls

A plausible explanation of these results advanced by Dell'Acqua et al. (2001) is schematically reproduced in Fig. 1. The model rests on two assumptions. The first assumption is related to the cause of the PRP effect. It is assumed that the PRP effect is explained by a central postponement model (Welford 1959; Pashler 1994). According to this model, RT_2 at short SOA is inflated by a period of suspension during which limited-capacity central mechanisms are busy with T_1 processing. In this view, part of the processing required for T_2 is postponed until these mechanisms are no longer occupied with T_1 processing. Likely operations engaging central mecha-

nisms in speeded choice-RT tasks include response selection (RS; McCann and Johnston 1992; Pashler and Johnston 1989; Schubert 1999; Van Selst and Jolicoeur 1997; Van Selst et al. 1999). The second assumption pertains to the effect of CHI. The impact of a CHI on choice-RT performance is a selective prolongation of the time required by central mechanisms for RS (see also Miller 1970). As is clear in Fig. 1, a temporal prolongation at a central stage of processing increases the period of suspension, thus inflating RT_2 at short SOAs between T_1 and T_2.

This explanation was extended to account for the results of a second experiment (experiment 2) in which T_1 required a delayed report of briefly presented and masked visual letters presented in T_1. In this second experiment, one or three letters (T_1) were presented in each trial, followed by a tone (T_2) at one of two possible frequencies. Subjects were instructed to encode the letters in T_1 for report delayed at the end of the trial, and make a speeded response based on T_2 frequency. After the tone response, subjects typed the displayed letters on a keyboard with no speed pressure, and memory for the letters was assessed. The choice of T_1 was based on evidence suggesting that part of the processing required for the delayed report of masked visual information requires central processing (Dell'Acqua and Jolicoeur 2000; Wong 2002). Specifically, central processing is required for the *short-term consolidation* (STC) of sensory/perceptual representations into durable short-term memory (STM) traces available for the delayed report (Jolicoeur and Dell'Acqua 1998; see also Jolicoeur et al. 2000). The results indicated that RT_2 produced by CHI patients in the present visual encoding paradigm was longer than RT_2 produced by controls. Patients' memory for the letters was good, and comparable with that of controls. As in the previous experiment, CHI patients and controls both showed a PRP effect, i.e., RT_2 increased progressively as SOA was decreased. SOA effects were more substantial for CHI patients than controls, the more so as the number of to-be-reported letters was increased. The model proposed to account for these results, reported in Fig. 2, is a straightforward adaptation of the model shown in Fig. 1 to the experimental context of the visual encoding paradigm.

Simply put, given the functional analogy between RS and short-term consolidation operations (i.e., both hypothesized to engage central mechanisms), postponement of RS_2 in this case is caused by ongoing central processing of T_1 for consolidation of the T_1 perceptual representation in a T_1 STM (reportable) trace.

The purpose of the present work is to provide empirical support for the notion that the most typical association of CHI symptoms discussed in the previous paragraphs (RT slowing and magnified dual-task impairments) has a unitary cause, namely, an increase in the time required for central processing of the stimuli. An additional aim of the present work is to generalize the account advanced in the context of the PRP and visual encoding studies of Dell'Acqua et al. (2001) to a different

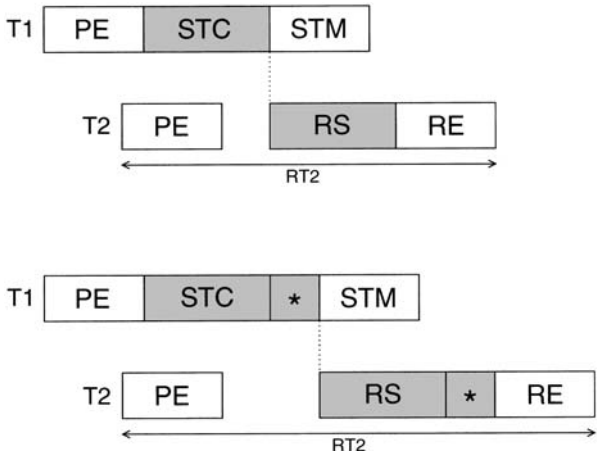

Fig. 2 Stage diagrams showing the interaction between mental operations in a visual encoding paradigm (experiment 2; Dell'Acqua et al. 2001) in conditions of high temporal overlap between tasks (i.e., at short SOAs), for both control subjects (*upper two diagrams*) and CHI patients (*lower two diagrams*). *PE* Perceptual encoding, *STC* short-term consolidation; *RS* response selection, *STM* short-term memory; *RE* response execution. Postponement of RS_2 in this case is caused by ongoing central processing of T_1 for consolidation of T_1 perceptual representation in a T_1 STM (reportable) trace

experimental context in which a novel combination of tasks was used. Two experiments were designed for this purpose.

The rationale for these experiments was similar to that underlying Dell'Acqua et al.'s (2001) experiment 2, with one important exception. In each trial of the present experiments, two stimuli requiring central processing were presented sequentially, separated by an SOA ranging from 350 to 1,550 ms. The first stimulus, T_1, was composed of briefly presented and masked visually displayed characters. In half of the trials in each experiment, these characters were to be encoded into STM for delayed report; in the other half of the trials, the characters could be ignored. In both experiments, a tone varying in frequency (either high or low) was presented as the second stimulus, T_2. Participants were instructed to press one of two buttons based on the tone frequency. When T_1 was associated with delayed report, subjects typed on the keyboard of a computer the characters presented in T_1 after responding to T_2. Memory for the characters in T_1 was assessed in terms of proportion of characters correctly reported at the end of each trial. The task in T_2 was a speeded task, and a reaction time (RT_2) was recorded in each trial. In experiment 1, ignore-T_1 trials and encode-T_1 trials were grouped into separate blocks of trials. In experiment 2, ignore-T_1 trials and encode-T_1 trials were intermixed at random in each block of trials.

The ignore-T_1 trials were included in the present experiment 1 and experiment 2 in order to test a fundamental issue concerning SOA effects on RT_2 that was left unresolved in the previous dual-task studies reported by Dell'Acqua et al. (2001). Given the lack of

any explicit requirement for reporting T_1 in ignore-T_1 trials, it was assumed that no central operations for T_1 processing were engaged under these conditions. If this were so, SOA effects were expected to be generally null on RT_2, with the only expected difference between CHI patients and controls under ignore-T_1 conditions being that relative to CHI RT_2 slowing. That is, if central mechanisms were not shared by the two tasks (as assumed in ignore-T_1 trials), no CHI magnification of dual-task costs was expected on RT_2.

Naturally, a direct comparison of ignore-T_1 versus encode-T_1 trials would be more relevant to this issue. Thus, in the present studies, the same combinations of tasks was required for T_1 and T_2 as in Dell'Acqua et al.'s (2001) experiments, but the task in T_1 was systematically varied. For half of the trials, the set of mental operations for T_1 processing could be confidently assumed to include the set of mental operations hypothesized in Fig. 2 (PE $\rightarrow$STC $\rightarrow$STM) in encode-T_1 trials. For the other half of the trials, a different set of mental operations was required, by assumption, when T_1 must be ignored. We anticipated that PE would still operate following T_1 presentation, but processing "downstream" would be unnecessary in ignore-T_1 trials and therefore presumably averted (Jolicoeur and Dell'Acqua 1998). Although the nature of processing in "no-go" trials is still debated (see Van Selst and Johnston 1997; Van Selst and Jolicoeur 1997), and an investigation of this is beyond the scope of the present work, it would suffice in the present context that different sets of mental operations had to be carried out on T_1 across different trials of the present experiments. Testing whether switching effectively between sets of mental operations is possible for CHI patients to the same degree as is for uninjured subjects was a unique opportunity provided by the following experiments.

General method

In this section of the paper, common aspects of the methods used in experiments 1 and 2 are described. These aspects are then integrated with details provided in the individual method sections reported at the beginning of each experiment's description.

Subjects

The present experimental investigation has been performed in accordance with the principles stated by the ethics committee of the Italian Association of Psychology (AIP) and is in complete accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. All persons involved in the present experimental investigation gave their informed consent prior to their inclusion in the CHI group and control group of subjects.

A group of eight CHI patients (two men and six women), and a group of eight uninjured controls were the subjects of the experiments. Demographic and clinical data for the patients are reported in Table 1.

The CHI group was selected from referrals at the Seregno Hospital using the following criteria: definite evidence of an acceleration–deceleration CHI, no use of drugs or medicines, no residual visual or motor deficit, no obvious reason for non-return to work, no seeking financial compensation for the injury, no pursuing litigation, severe CHI with Glasgow Coma Scale (GCS; Jennett and Bond 1975) scores between 3 and 8 at admission in the rehabilitation unit (between 2 and 6 months after trauma). The post-traumatic amnesia (PTA) was estimated using the GOAT scale (Levin and Grossman 1979). PTA duration was assessed by interviewing patients and relatives. Patients with PTA duration of 7 days or longer were considered ideal candidates during the selection process. CHI and control subjects with a history of alcoholism, psychiatric disorder, mental retardation, or neurological disease were excluded. Magnetic resonance imaging (MRI) was carried out for three patients only, with two of the patients exhibiting diffuse axonal injury.

The selected patients had undergone traditional neuropsychological assessment. Memory was assessed by Corsi block tapping and story recall. Attention was assessed by forward and backward digit span and attentive matrices. Executive functions were assessed by phonemic and categorical verbal fluency. All patients showed equivalent points (Spinnler and Tognoni 1987) in the normal range as assessed by the administration of Raven's progressive matrices (A, B form). No abnormalities were found in the WAIS subtests assessing reasoning and concept formation skills. All tests were administered according to standard published protocols or established procedures. Despite the apparently good recovery, all the patients continued to have broadly defined complaints, such as difficulty in concentration, fatigue, irritability, and difficulty in performing tasks at the same level as they did before trauma. Furthermore, five of them could not resume work or study.

The mean age and education of CHI patients were 29 years and 13 years, respectively. The mean Glasgow Coma Scale score at hospital admission was 5.1, and the mean coma duration was 13 days. All CHI patients were tested between 5 and 41 months after injury. The control group was matched for sex, age (mean 30 years, SD 9 years), and years of education (mean 13 years, SD 4 years). Controls and CHI patients did not show significant

Table 1 Demographic and clinical features of CHIs. [*N* arbitrary numbers assigned to CHI patients, *Educ.* years of education,*GCS* Glasgow Coma Scale scores (at admission in the rehabilitation unit), *PTA* Post-traumatic amnesia (GOAT scores), *Time* time post-injury interval]

N	Sex	Age (years)	Educ. (years)	GCS	Coma duration (days)	Lesions (CAT scan)	PTA (days)	Time (months)
1	F	21	13	3	7	Left frontal and right temporal	28\	6
2	F	36	8	6	7	Bilateral frontal	7	28
3	M	26	17	8	15	Left temporal	26	12
4	F	20	10	4	13	Bilateral frontal, right temporal and left parietal	30	41
5	M	25	16	5	40	Bilateral frontotemporal and right parietal	50	33
6	F	34	13	5	15	Frontal and diffuse axonal injury	25	5
7	F	25	13	4	5	Left temporal	34	9
8	F	50	5	6	6	Diffuse axonal injury	8	5

differences in any of these variables (age: $t(14) = 0.178$, $P = 0.66$; education: $t(14) = 0.027$, $P = 0.89$).

All the subjects (CHI patients and controls) were right-handed, naive to the specific purpose of the experiments, had normal or corrected-to-normal vision, and gave informed consent.

Materials

Visual stimuli

The visual stimuli were black (7 cd/m^2) uppercase characters presented on a light-gray background (28 cd/m^2), on a SVGA computer screen (cathode ray tube) controlled by a 586 CPU. The characters could be letters (all except A and Z) or digits (all except 0 and 1). In both the present experiments, the characters were exposed for 250 ms, and each character was then masked for 100 ms by superimposed O and $ characters. The characters were displayed at the center of the computer screen, and subtended 0.85 (height) × 0.80 (width) degrees of visual angle at a distance of 60 cm set by a chin-rest. When more than one character was displayed, the characters were arrayed horizontally, and the space between adjacent characters was 0.10° of visual angle. The characters were randomly selected, without replacement, from the set of available characters in each trial.

Auditory stimuli

The auditory stimuli were pure tones, presented for 85 ms, with a frequency of 400 Hz or 1,200 Hz. The auditory stimuli were presented through the speakers of the computer, with the volume set to be always clearly audible (~50 dB).

Procedure

Both experiments were carried out in a dimly lit, sound-attenuated room, in the presence of a research assistant, who paced the trial presentation sequence and controlled the length of the practice phase preceding the data-recording phase. In each trial of the present experiments, two stimuli were presented in succession, with each stimulus associated with a distinct task. The first stimulus (T_1) was a visual stimulus, and the second stimulus (T_2) was an auditory stimulus. In half of trials in each experiment, the visual stimulus could be ignored. In the other half of trials, the visual stimulus was associated with a delayed report. The second stimulus in each experiment always required a speeded response. Each trial began with the presentation of a message at the center of the screen indicating the number of characters to be displayed (i.e., "ONE CHARACTER" or "THREE CHARACTERS"). Each trial was initiated by the assistant, who pressed one button on the mouse connected to the CPU. Following the mouse-button press, the message disappeared, and after a fixed delay of 600 ms, one or three characters (always corresponding to the number of characters reported in the initial message) were displayed, and then masked. At varying SOAs (either 350, 900, or 1,550 ms) following the characters, a tone was presented, and subjects were instructed to make an immediate, two-alternative forced-choice response based on the tone pitch. The subjects pressed the *A* key of the computer keyboard with the middle finger of their left hand if the pitch of the tone was high (1,200 Hz), or the *Z* key with the index finger of their left hand if the pitch of the tone was low (400 Hz). The subjects were instructed to keep the designated fingers continually resting on the *A* and *Z* keys during the entire experiments, and to respond to the tone as quickly as possible, while keeping errors to a minimum. After the execution of the speeded tone response, and under conditions in which subjects were instructed to remember the characters, subjects had to type on the keyboard the displayed characters, guessing when uncertain. The subjects always typed in as many characters as they were presented with. When the characters could be ignored, the subjects were instructed to press the spacebar after the tone response. In each experiment, levels of SOA, number of characters, and tone frequency were fully randomized within each block of trials.

Method of analysis

In each trial, one response to the characters and one response to the tone were produced. When the characters had to be remembered and recalled, responses to the characters were scored in terms of percentage of letters correctly reported at the end of each trial, with no regard of order of report when more than one character was displayed in a given trial. Responses to the tone were scored in terms of speed (RT) and accuracy (proportion of correct-tone responses). Only tone RTs associated with a correct response were included in the analyses. Correct-tone RTs were screened for outliers using a modification of the procedure described by Van Selst and Jolicoeur (1994). The tone RT data in each cell, for each subject, were sorted, and the most extreme observation was temporarily excluded from consideration. The mean (M) and standard deviation (SD) of the remaining data points were then computed. Cutoff values were established using the following equations:

$$V_{low} = M - C^{*}SD \quad V_{high} = M + C^{*}SD,$$

where C was a parameter that depends on sample size (see Van Selst and Jolicoeur 1994), such that the final estimate of sample means was not influenced by sample size. The smallest and largest observations were then checked against the cutoff values, and treated as outliers if one or both of these observations exceeded V_{low} or V_{high} values. The algorithm was applied recursively to the data set until no outliers were found. The percentage of outlier RTs excluded following the application of the present algorithm is reported in the individual method section of the experiments.

Experiment 1

A set of detailed predictions can be made on the assumption that *central processing slowness* is the sole deficit of CHI patients in performing these tasks. In encode-T_1 trials, memory for the characters should be comparable between CHI patients and controls. As previously observed with both CHI patients (Dell'Acqua et al. 2001) and uninjured subjects (Jolicoeur and Dell'Acqua 1998), an exposure duration of 250 ms provides ample time to generate a reportable STM trace for the characters used in the present experiments. Furthermore, perceptual processing and maintenance in STM are generally assumed to be preserved in CHI patients (Van der Linden et al. 1992).

Compared with controls, however, CHI patients should generally take longer to emit the speeded response to T_2. Furthermore, since each task in these paradigms required serial central processing of the stimuli, slowing of RT_2 is expected, for both CHI patients and controls, at short SOA compared with long SOA, due to the functional interaction depicted in Fig. 2. More importantly for present purposes, SOA effects should be more pronounced for CHI patients than for controls, under conditions in which the characters had to be encoded into STM via consolidation. This pattern was expected based on the assumption that any central operations performed by CHI patients should take longer than analogous operations performed by controls. We also

expected this dual-task cost to be even more pronounced in cases in which the number of to-be-reported letters was 3, instead of only 1. However, when central operations were not necessary for the task on the T_1 characters, as when the T_1 characters could be ignored, no difference between CHI patients' and controls' performance, apart from the predicted slowing effect, was expected on RT_2.

Method

In each trial of the present experiment, one or three letters were presented and then masked. During the data-recording phase, subjects performed 8 blocks of 24 trials each. The beginning of each block was preceded by written instructions that were displayed on the monitor of the computer, indicating the type of task required for the letters. In half of the blocks, subjects were instructed to remember the letters for later report at the end of each trial. In the other half of the blocks, subjects were instructed to ignore the letters (whilst still fixating the center of the monitor). The order of block types was randomized for each subject, with the constraint of having to perform no more than two blocks with the same instructions (ignore versus encode) consecutively. In each trial, the tone was presented at one of three SOAs following the letters, and subjects had to press, as quickly and accurately as possible, one of two keys on the computer keyboard based on the tone pitch. After the tone response, and only when instructed to remember the letters, subjects had to type the letters on the computer keyboard, guessing when uncertain. The letter-report task was carried out with no speed pressure. When instructed to ignore the letters, subjects pressed the spacebar after the tone response in order to continue with the beginning of the next trial. Participants performed a variable number of practice trials before the data recording phase. The number of practice trials ranged from a minimum of 32 to a maximum of 64. After each block of experimental trials, subjects were invited to take a short rest before beginning with the next block of trials.

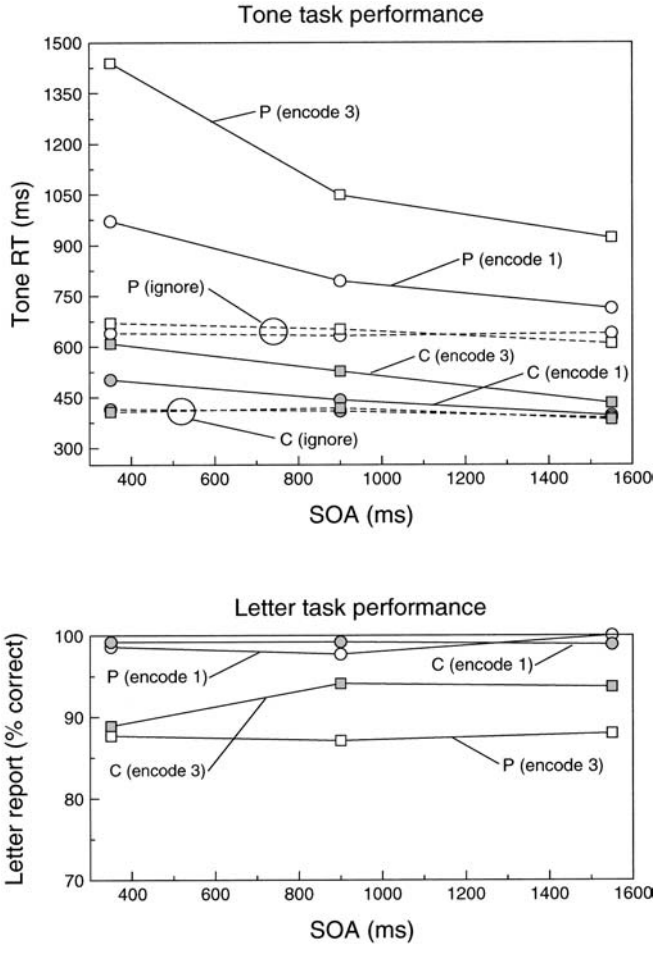

Fig. 3 Summary of the results of experiment 1. *Upper panel:* Mean RTs in the tone task, as a function of SOA, as a function of the number of letters [*1* one letter (*square symbols*); *3* three letters (*circle symbols*], as a function of population sample [*P* CHI patients (*open symbols*); *C* controls (*filled symbols*)], and as a function of the type of task associated with the letters [encode (*solid lines*); ignore (*dashed lines*)]. *Lower panel:* Mean proportion of letters correctly reported at the end of each trial, as a function of the number of letters, and as a function of population sample

Results

A summary of the results is reported in Fig. 3. The mean percentage of letters correctly reported (lower panel) and mean tone RT (upper panel) are plotted separately as a function of the four factors examined within the present experimental design, i.e., population (CHI patients versus controls), SOA, number of letters displayed, and type of task on the letters (encode versus ignore the letters). All factors except population were treated as within-subject factors in the analyses of variance (ANOVAs) performed on the mean percentage of letters correctly reported, accurate tone response RT, and mean percentage of correct-tone responses, estimated for each subject in each cell of the present experimental design. The significance level was $P = 0.05$.

Letter report

An ANOVA on letter-report accuracy was carried out on data from the condition in which letters had to be recalled at the end of each trial (i.e., "encode" condition). The mean percentages of letters correctly reported by patients and controls (93% and 95%, respectively) were not significantly different. The percentage of letters correctly reported when one letter had to be encoded was significantly higher than the percentage of letters correctly reported when three letters had to be encoded [$F_{1,\ 14} = 23.0$, mean square error (MSE) = 85, $P < 0.001$]. No other factor or interaction involving the population factor reached the significance level.

Tone responses

The application of the outlier elimination procedure resulted in a total loss of 2.1% of correct-tone RTs. (All the analyses reported were also carried out with the inclusion of the outlier RTs, and the pattern of results did not change.) All four factors resulted in significant main effects in the ANOVA carried out on tone RTs. Mean

tone RTs for patients were longer than mean tone RTs for controls (811 versus 450 ms; $F_{1,14}$ = 13.0, MSE = 478,751, $P < 0.01$). The SOA manipulation produced a monotonic tone RT increase as SOA was shortened (from 569 ms to 707 ms; $F_{1,14}$ = 30.8, MSE = 10,151, $P < 0.001$). Slower tone RTs were observed when three letters were exposed than when one letter was exposed (578 versus 682 ms; $F_{1,14}$ = 21.6, MSE = 24,077, $P < 0.001$). Tone RTs were longer in the encode condition than in the "ignore" condition (739 ms versus 522 ms; $F_{1,14}$ = 26.7, MSE = 84,792, $P < 0.001$).

The population factor separately interacted with each of the remaining factors. Results indicated RT function slopes generally steeper for patients than for controls as SOA was shortened ($F_{2,28}$ = 9.1, MSE = 10,151, $P < 0.001$). Effects on tone RTs of the type of task performed on the letters were more pronounced for patients than for controls ($F_{2,28}$ = 8.7, MSE = 84,792, $P < 0.001$). Also the effect on tone RTs of the number of letters was more pronounced for patients than for controls ($F_{2,28}$ = 5.9, MSE = 24,077, $P < 0.03$).

The four-way interaction among the factors considered in the present experimental design was significant ($F_{2,28}$ = 3.9, MSE = 2,876, $P < 0.03$). As the results reported in the upper panel of Fig. 3 suggest for the encode condition, tone RTs increased more rapidly as SOA was shortened in the three-letter condition than in the one-letter condition. This pattern was more pronounced for patients than for controls. In the ignore condition, tone RTs were longer for patients than for controls. In this task condition, however, tone RT functions were substantially flat across SOAs and not affected by the manipulation involving the number of letters. In order to distinguish the sources of this complex interaction, the data from the ignore and encode task conditions were analyzed separately. The results from the ignore condition revealed a main effect of population ($F_{1,14}$ = 8.7, MSE = 154,622, $P < 0.02$), with no other factor reaching the significance level. The results from the encode condition revealed a significant main effect of population ($F_{1,14}$ = 13.8, MSE = 408,920, $P < 0.003$), a significant main effect of SOA ($F_{1,14}$ = 31.0, MSE = 16,709, $P < 0.001$), and a significant main effect of number of letters ($F_{1,14}$ = 21.1, MSE = 48,040, $P < 0.001$). The three-way interaction among all factors considered in this separate analysis was significant ($F_{2,28}$ = 5.6, MSE = 6,654, $P < 0.01$), reflecting the magnified SOA effect on tone RTs for both the one-letter condition and the three-letter condition for patients compared with controls. In order to provide an additional test of the different impact of the SOA manipulation on patients' performance and on controls' performance, the data from the one-letter condition and those from the three-letter condition when letters had to be encoded were analyzed separately. A significant interaction between SOA and population was detected in both the one-letter condition and the three-letter condition ($F_{2,28}$ = 4.7, MSE = 5,364, $P < 0.02$ and $F_{2,28}$ = 10.3, MSE = 17,999, $P < 0.001$, for the one-letter condition and three letter condition, respectively).

The mean percentage correct in the tone task was 98% for patients and 95% for controls. Error rates were analyzed as a function of the same factors considered in the tone RT analyses. The manipulation involving the number of letters produced a significant effect ($F_{1,14}$ = 8.5, MSE = 0.003, $P < 0.02$), with less accurate tone responses in the three-letter condition (95%) than in the one-letter condition (98%). No other factor or interaction reached the significance level.

Discussion

The results of experiment 1 fit all the predictions described above. Memory for the letters presented in T_1 was generally stable across SOAs, and comparable across CHI patients and controls. However, CHI patients were generally slower than controls in performing the speeded task in T_2, a result that closely resembles the results of experiment 2 reported in Dell'Acqua et al.'s (2001) study. In encode-T_1 trials, the manipulation of the number of to-be-recalled letters presented in T_1 had a stronger impact on CHI patients' performance than on controls' performance in RT_2, that is, the SOA-locked difference between the one-letter and three-letter conditions was more pronounced for CHI patients than for controls. In ignore-T_1 trials, on the other hand, no SOA effects manifested in RT_2. That is, the only significant difference between CHI patients and controls was that relative to the expected RT_2 slowing produced by the hypothesized CHI impact on speeded task performance, i.e., the longer time taken by central mechanisms to carry out RS. Thus, the results from ignore-T_1 trials suggest that CHI patients, as well as controls, could effectively inhibit central processing when such processing was unnecessary, i.e., as in ignore-T_1 trials.

Experiment 2

The results of experiment 1 are congruent with the hypothesis of a unitary source for RT slowing and magnified dual-task slowing in CHI patients. However, the results do not conclusively demonstrate that CHI patients are fully capable of switching between mental sets as demanded by the different T_1 task in ignore-T_1 and encode-T_1 trials. One might argue that dividing these different trials into separate blocks, as in the present experiment 1, did not provide the most challenging test of CHI patients' ability to abandon one mental set (e.g., one required for encoding information into STM) in favor of another one (i.e., the one required for ignoring). In this vein, CHI patients could have become practiced in adopting a specific mental set only after some trials within the same block had been performed consecutively.

Experiment 2 was designed to address the issue of control more directly. Within each block of trials of experiment 2, three letters or three digits were presented with equal probability in the T_1 position (see below for

details). The task in T_1 was different on these characters. Subjects were instructed to ignore the digits, and report only the letters. Unlike in experiment 1 therefore, subjects could not anticipate what kind of task had to be performed in T_1 before T_1 was physically present on the monitor. Under these specific conditions, mental switching had to occur on a per-trial basis and in the absence of advanced preparation, instead of being maintained throughout a block of equivalent trials as in experiment 1.

Method

In the present experiment, three characters were always presented at the beginning of each trial and then masked. With equal probability in each trial, the characters could be digits or letters. The task associated with the characters was contingent on the identity of the characters. Subjects were instructed to ignore the digits and encode the letters for delayed report at the end of each trial. At one of three SOAs following the characters, a tone was presented at one of two possible pitches, and subjects had to press, as quickly and accurately as possible, one of two keys of the computer keyboard based on the tone pitch. After the tone response, and only when letters were exposed, subjects had to type the letters on the computer keyboard, guessing when uncertain. The letter-report task had to be carried out with no speed pressure and, in each trial, three letters had to be typed on the keyboard. When digits were exposed, subjects pressed the spacebar after the tone response in order to continue with the beginning of the next trial. Participants performed a variable number of practice trials before the data-recording phase. The number of practice trials ranged from a minimum of 24 to a maximum of 48. Each subject performed in 216 experimental trials, which were divided into 9 blocks of 24 trials each. After each block of experimental trials, subjects were invited to take a short rest before beginning with the next block of trials.

Results

A summary of the results is reported in Fig. 4. The mean percentage of letters correctly reported (lower panel) and mean tone RT (upper panel) are plotted separately as a function of the three factors examined within the present experimental design, i.e., population (CHI patients versus controls), SOA, and type of task on the characters (encode letters versus ignore digits). All factors except population were treated as within-subject factors in ANOVAs performed on the mean percentage of letters correctly reported, correct-tone response RT, and mean percentage of correct-tone responses, estimated for each subject in each cell of the present experimental design.

Letter report

An ANOVA on letter-report accuracy was carried out on data from the "letter-encode" condition. The mean percentages of letters correctly reported by patients and controls (86% and 94%, respectively) differed significantly ($F_{1,14} = 6.8$, MSE = 110, $P < 0.03$). No other factor or interaction reached the significance level.

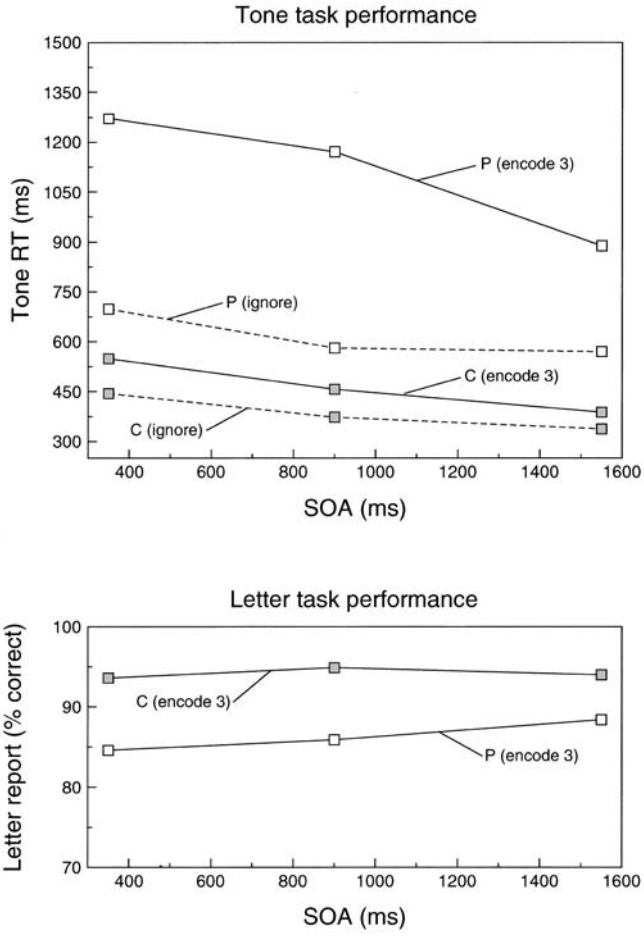

Fig. 4 Summary of the results of experiment 2. *Upper panel:* Mean RTs in the tone task, as a function of SOA, as a function of population sample [*P* CHI patients (*open symbols*); *C* controls (*filled symbols*)], and as a function of the type of task associated with the characters [letter-encode (*solid lines*); digit-ignore (*dashed lines*)]. *Lower panel:* Mean proportion of letters correctly reported at the end of each trial as function of population sample

Tone responses

The application of the outlier elimination procedure resulted in a total loss of 2.8% of correct-tone RTs. All three factors resulted in significant main effects in the ANOVA carried out on tone RTs. Mean tone RTs for patients were longer than mean tone RTs for controls (863 versus 425 ms; $F_{1,14} = 9.6$, MSE = 480,654, $P < 0.008$). The SOA manipulation produced a monotonic increase in tone RT as SOA was shortened (from 546 to 740 ms; $F_{1,14} = 54.4$, MSE = 5,544, $P < 0.001$). Tone RTs were longer in the letter-encode condition than in the "digit-ignore" condition (787 versus 501 ms; $F_{1,14} = 16.4$, MSE = 120,245, $P < 0.002$).

All two-way interactions among the factors considered in the present experimental design gave rise to significant effects. The three-way interaction between these factors was also significant ($F_{2,28} = 5.4$, MSE = 6,035, $P < 0.02$). As the results reported in the upper panel of Fig. 4 suggest

for the letter-encode condition, tone RTs increased more rapidly as SOA was shortened for patients than for controls relative to comparable SOA effects that were strongly reduced in the digit-ignore condition. Separate analyses were carried out on data from the letter-encode condition and from the digit-ignore condition. In the digit-ignore condition, the analysis revealed a significant main effect of population ($F_{1, 14} = 9.1$, MSE = 70,813, $P < 0.01$), a significant main effect of SOA ($F_{1, 14} = 23.0$, MSE = 2,660, $P < 0.001$), and no interaction between these two factors ($F < 1$). The RT difference between patients and controls at each SOA level was 242 ms, 208 ms, and 254 ms at SOA = 1,550 ms, SOA = 900 ms, and SOA = 350 ms, respectively. In the letter-encode condition, the analysis revealed a significant main effect of population ($F_{1, 14} = 9.4$, MSE = 530,087, $P < 0.009$), a significant main effect of SOA ($F_{1, 14} = 34.0$, MSE = 8,918, $P < 0.001$), and a significant interaction between these two factors ($F_{2, 28} = 7.1$, MSE = 8,918, $P < 0.004$). The RT difference between patients and controls at each SOA level was 500 ms, 704 ms and 722 ms at SOA = 1,550 ms, SOA = 900 ms, and SOA = 350 ms, respectively.

The mean percentage correct in the tone task was 98% for patients and 96% for controls. The error rates were analyzed as a function of the same factors considered in the tone RT analyses. No factor or interaction reached the significance level.

Discussion

The results of experiment 2 were clear-cut. In encode-T_1 trials, both CHI RT general slowing, magnified dual-task costs (i.e., greater SOA effects) and good level of memory for the to-be-reported letters found in experiment 1 were entirely replicated in experiment 2. Critical for the present purposes were the results from ignore-T_1 trials. The results from ignore-T_1 trials highlight a crucial similarity between CHI patients' and controls' performance in the speeded task. That is, apart from an expected slowing affecting CHI responses, no difference in the size of SOA effects between CHI patients and controls were detected in RT_2. As argued in the introduction to the present experiment, and as will be discussed more in details in the General Discussion, the results from experiment 2 suggest that, under the present experimental conditions, CHI patients did not exhibit any disorder of attentional control. The results from ignore-T_1 trials show that, even when the cognitive machinery must be reset trial to trial, CHI patients were not subject to any increased dual-task costs. The functional source of the small SOA effect on RT_2 for both CHI patients and controls is not clear. Although this small SOA effect may in principle be attributed to a late stage of categorization of the visual stimuli into the to-be-encoded class or to-be-ignored class of stimuli just prior the short-term consolidation stage required for the delayed report, other potential explanations may be advanced to account for this unexpected result. For instance, it might be that, despite the instruction to ignore the T_1 digits, subjects failed to do so and encoded T_1, in some small proportion of trials, as though T_1 was composed of letters. In the present design, there clearly was no way to distinguish these different possibilities, insofar as memory for the characters was strategically assessed only when characters were letters, and not otherwise. However, independently of the source of this specific SOA-locked pattern detected in RT_2, the relative effects produced in the speeded task performance in ignore-T_1 trials were, under conditions of minimal involvement of central mechanisms for the task in T_1, identical between CHI patients and controls.

General discussion

Comparison with previous CHI models

The present experiments provide two important demonstrations. The first demonstration is related to the functional locus of CHI. In both experiments, the CHI patients showed an abnormal SOA-locked deficit in emitting a speeded response to an auditory stimulus when the auditory stimulus followed a visual stimulus requiring a delayed report. We argue that these results are strong evidence of the involvement of central mechanisms in producing both the general slowness that usually characterizes CHI patients' speeded responding and the enlarged, dual-task performance decrement observed with the use of chronometric tasks (see models in Figs. 1 and 2). The second demonstration suggests a different picture of the dual-task CHI disorder than most researchers in this field have advocated. Whereas past studies in the dual-task domain have assumed that CHI patients suffer from an independent attentional control disorder, the present study provides no support for this assumption. CHI patients were fully capable of planning in advance and coping with a rather complex and arbitrary sequence of responses, such as that implicated in the execution of the present visual encoding paradigms. CHI patients' ability to switch between mental sets (i.e., those required for encoding or ignoring the visual information presented in T_1) was evident both in experiment 1, where a mental set had to be maintained throughout a series of similar trials, and in the more challenging experiment 2, where the mental set required for T_1 processing was varied unpredictably trial to trial.

It might be worth mentioning that the preservation of attentional control in CHI patients can be reconciled with observations about the impact of a CHI in everyday activities, and particularly those involving multiple tasks. For example, it has been proposed that overall driving safety is likely to be preserved following a diffuse neurological disease, if evaluation of risks and the corresponding control of actions are demonstrably unimpaired (Van Zomeren and Brower 1987). Unlike the present visual encoding tasks, driving is not a self-paced activity, but largely paced by external events. In situations

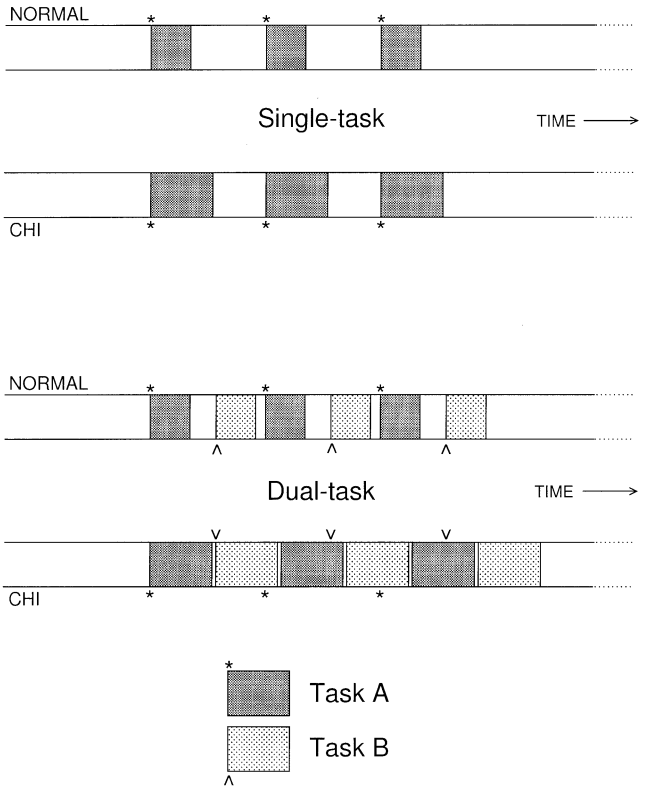

Fig. 5 Exemplification of a potential reflection of *CHI central processing slowness* on multitasking performance with stimuli (*asterisks* and *arrows*) arriving at regular intervals over a relatively extended period of time. *Top:* Single-task condition. Provided sufficient time elapses between successive stimuli, both CHI patients and normals can begin with task A in coincidence with stimulus arrival, and finish task A before the next stimulus presentation. *Bottom:* Dual-task condition. Normals can maintain a correct sequence of task A and task B responses to the double stimulation (finishing either task before the next stimulus arrives), whereas CHI patients are still busy with responding to previous stimuli when new stimuli are presented

of that kind, central slowing may produce serious failures of performance in multitasking conditions that require more prompt responding than CHI patients can cope with. Figure 5 provides an example of how this might happen.

Consider one task (task A) that is elicited by stimuli arriving once per second. Under single-task conditions, both CHI patients and uninjured subjects can readily keep up with the arrival of new stimuli so long as the interval separating the stimuli is sufficient to perform task A. However, when two tasks (task A and task B) must be performed, for CHI patients the probability that stimuli will arrive when processing for the other task is still under way will be elevated. The result—catastrophic breakdown in performance—is likely to be indistinguishable from that caused by a control disorder.

Examination of alternative accounts

As described briefly in the Introduction, our proposal that central processing is the principal cause of both CHI RT slowness and magnified multitasking cost is directly derived from models of the PRP effect based on the idea of a single-channel limitation in central processing (Pashler 1994). There are alternative interpretations of the PRP effect, however. For example, Gottsdanker (1980) and Koch (1995) proposed that the PRP effect stems from fluctuations in level of task preparation, with reduced preparation for the second stimulus at short SOAs. In this account, the PRP effect occurs because preparation is divided between the two speeded tasks (and therefore diminished) at short SOAs, whereas each task is fully prepared when the SOA is long. If this account is correct (see Pashler 1998, for evidence against it), our results would imply that CHI patients were less prepared for the speeded task at short SOA than controls. Another model that dispenses with the idea of a structural central bottleneck was proposed by Meyer and Kieras (1997) in their executive-process interactive control (EPIC) architecture. In this view, the PRP effect reflects a strategy used by subjects to cope with the explicit requirement to maintain a particular response order under PRP conditions. In Meyer and Kieras's (1997) terms, the PRP reflects the adoption of a "cautious" in contrast to a "bold" strategy in which serial processing occurs even when parallel processing would be possible. In this analysis, our results would imply that CHI patients are more often cautious than controls (perhaps because they are generally more prone to making errors). Finally, it has also been noted that dual-task interference might be due in part to limitations that are structural but not central. Examples would include bottlenecks in response initiation or production (De Jong 1993; Keele 1973). In such accounts, our results would suggest that CHI patients' performance may stem from increased difficulty in motoric processing stages when the speeded response had to be emitted closely after the presentation of a to-be-encoded visual stimulus.

While such accounts might allow one to make sense of some of the present results, they collide with recent empirical evidence collected in studies involving healthy adults (Levy and Pashler 2001; Ruthruff et al. 2001, 2003). Furthermore, they offer no easy way to account for the present finding of a sizable PRP effect in the case where only a single speeded response was required in each trial and primary emphasis was placed on the speed with which this task was carried out. Here, it stands to reason that subjects would be quite fully prepared for the speeded task in order to react as soon as possible to the imperative signal. Support for this assumption comes from the fact that, in experiment 2, only the general RT slowing effect was observed when subjects had to unpredictably ignore the primary visual stimulus. The fact the CHI patients' and controls' performance was unaffected by SOA variations under these conditions in experiment 2 strongly suggests that

CHI patients were at least as able as controls to maintain a constant level of preparation for the speeded task across SOAs. This is problematic for the idea that a preparation deficit is the source of the magnified dual-task costs observed in the present study (Gottsdanker 1980; Koch 1995). Thus, the present results suggest that preparation played a minimal role in modulating CHI patients' performance in the present experiments. The strategic interpretation of Meyer and Kieras (1997) is also hard to apply to the interference observed here, since only a single speeded task was to be executed in a trial. The response associated with the speeded task was always executed before the (delayed, unspeeded) response associated with the visual encoding task, and primary emphasis was always placed on the speeded task. Thus, it is hard to see where the "caution" proposed by these authors would enter the picture. This also suggests that other forms of cross-task interference (e.g., motoric interference as suggested by De Jong 1993, and Keele 1973) cannot account for the present results. Furthermore, the fact that the delayed visual encoding task was the one associated with the second response would seem to imply that, had strategic deferment played any role in modulating subjects' performance in experiment 1 and experiment 2, such modulation should have been manifested as a memory deficit in the visual encoding task. Experiment 1 and experiment 2 provide neither conceptual nor empirical support for this view.

CHI and attentional disorders

In the Introduction, we noted that most neuropsychologists tend to view dual-task costs in CHI as resulting from a disorder of attention control, independent of the ubiquitous slowness exhibited by patients with this condition (Park et al. 1999; Stablum et al. 1994, 1996, 2000). This would fit with the view that successful execution of concurrent tasks depends on executive coordination, with failures of coordination resulting in errors, action slips, or delayed responses (as seen most clearly in the task switching literature; cf. Allport et al. 1994; Monsell 1996; Rogers and Monsell 1995). A strong interpretation of our findings would instead suggest that the CHI patients' performance impairment in multitasking performance (i.e., the exacerbated PRP effect observed in experiments 1 and 2) reflects the very same problem as that manifested in their single-task performance, namely a slowing of central processing.

In a previous subsection of the General Discussion, we discussed in some detail one way that our view may be partially reconciled with the control disorder interpretation (see Comparison with previous CHI models). In our account, the extra multitasking cost found here reflects the fact that one task waits for another task. Even if that is so, it is still possible that CHI patients may show additional disorders above and beyond those attributable to central slowing, when placed in multitasking situations demanding more active coordination or preparation than do the PRP-like tasks studied here. These paradigms required subjects to carry out two discrete tasks in each of a series of trials. Subjects were invited to take their time between trials in order to be fully prepared for stimuli arrival before the trial started (and they had the opportunity to initiate each trial whenever they were ready, by nodding at the research assistant). Compare this with a study by Robertson et al. (1997), which found evidence suggestive of a control disorder in CHI. These authors focused on the ability of CHI patients to maintain a complex attentional set over a significant period of time. In a procedure labeled "sustained attention to response test" (SART), 225 digits were presented visually, one at a time, in one of five possible locations on a computer screen. Subjects were invited to make key-presses to each digit, except to the digit "3", which was designated a no-go stimulus. Interestingly, CHI patients tended to miss the target stimulus and produced a speeded response to 3 more frequently than controls. It is possible that the key difference between this study and our PRP-like designs is the fact that, in the former study, the presentation of stimuli could not be interrupted by the subject. This was done deliberately, of course, in order to assess CHI performance in conditions of sustained attention. In any case, this study clearly suggests that other aspects of attentional performance (in the case examined, sustained maintenance of an attentional set) can be compromised in CHI patients in a way that does not appear to be mediated by central slowing.

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