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ORIGINAL ARTICLE

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A neuropsychological assessment of dual-task costs in closed-head injury patients using Cohen's effect size estimation method

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Abstract A test of whether patients suffering from a severe closed-head injury (CHI) were affected by disproportionate dual-task costs compared to those of healthy control participants was carried out through a direct comparison of CHI effects on dual-task (psychological refractory period, or PRP) performance and on single-task performance. In the dual-task condition of the present experiment, independent choice-responses were required to two sequential stimuli presented at a variable stimulus onset asynchrony (SOA). A significant delay of the reaction time (RT) to the second stimulus was reported by both CHI patients and controls at short (SOA) compared to long SOA, i.e., a PRP effect. The PRP effect was more pronounced for CHI patients than controls. In the single-task condition, a single choice-response was required to a stimulus presented in isolation. The RT produced by CHI patients in the single-task paradigm was longer than the RT produced by controls. CHI effects on dual-task performance and on single-task performance were compared following (1) their transformation into Cohen's ds, and (2) the application of a correction algorithm taking into account the different reliability of single-task and dual-task measures. The analysis of Cohen's ds revealed that CHI effects on performance were, if anything, smaller in the dual-task condition than in the single-task condition. The results imply that CHI patient's slower responding in single- and dual-task performance reflects a single common cause—slowing of the central processing.

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Introduction

Neuropsychologists observing the symptoms that arise as a consequence of a severe closed-head injury (CHI) often report that CHI patient suffer from an exaggerated difficulty in coordinating multiple activities, as compared to that experienced by neurologically intact adults (Brooks, 1984). Multi-tasking deficits are sometimes observed in the performance of CHI patients even in the absence of a corresponding single-task deficit (Park, Moscovitch, & Robertson, 1999). This finding has led many neuropsychologists in this area of studies to infer that CHI deficits may reflect a selective impairment of executive functions, i.e., the class of mental operations held to be responsible for organizing and scheduling the distinct subsets of processing stages required for two or more overlapping tasks (Leclercq, Couillet, Azouvi, Marlier, Martin, Strypstein, & Rousseaux, 2000; Stablum, Leonardi, Mazzoldi, Umiltá, & Morra, 1994).

Dell'Acqua, Pashler, and Stablum (2003; see also Dell'Acqua, Stablum, Galbiati, Spannocchi, & Cerri, 2001) have recently examined empirically the issue of multi-tasking deficits in CHI patients, and proposed a unifying account of CHI effects under single-task and dual-task conditions. Using a standard psychological refractory period (PRP) paradigm (see Pashler & Johnston, 1998, for a review), these authors presented a group of CHI patients and a group of age-matched controls with two stimuli on each trial: a tone (T1) varying in frequency, and a circular pattern (T2) varying in color, separated by 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, RT1 (vocal, based on pitch) and RT2 (manual, based on color), respectively (response times measured from the corresponding stimulus presentation). The results indicated that both RT1 and RT2 produced by CHI patients were longer than RT1 and RT2 produced by controls. Moreover, both CHI patients and controls showed a classical PRP effect, i.e.,

SOA variation did not affect RT1, but as the SOA was shortened, RT2 was lengthened. Interestingly, while the magnitude of the PRP effect (RT2 at the shortest SOA–RT2 at the longest SOA) was greater for CHI patients, this increase corresponded closely to the overall slowing effect shown by CHI patients in RT1. Based on this finding, Dell'Acqua and colleagues proposed an account of the CHI impairment that is illustrated in Fig. 1.

Backed by a large set of empirical findings, the model assumes that the PRP effect is normally caused by central processing postponement (Welford, 1959; Pashler & Johnston, 1998). RT2 at short SOA is increased by a period of postponement during which limited-capacity central mechanisms are occupied with processing of T1. Corresponding stages of processing for T2 are postponed until the limited-capacity mechanisms are finished with T1 processing. One operation thought to engage central mechanisms in speeded choice-RT tasks is response selection (McCann & Johnston, 1992; Pashler & Johnston, 1989; Schubert, 1999; Van Selst & Jolicoeur, 1997), but in some tasks, other decision-related processes may also be subject to "bottlenecking" (see Pashler & Johnston, 1998, for a review). The second assumption pertains to the effect of CHI. The impact of a CHI on choice-RT performance is a slowing of the process of response selection (see also Miller, 1970). As Fig. 1 shows, a prolongation of T1 central processing increases the period of postponement, inflating RT2 at short SOAs between T1 and T2 and magnifying the PRP effect (defined as RT2 for a short SOA minus RT2 for a long SOA).

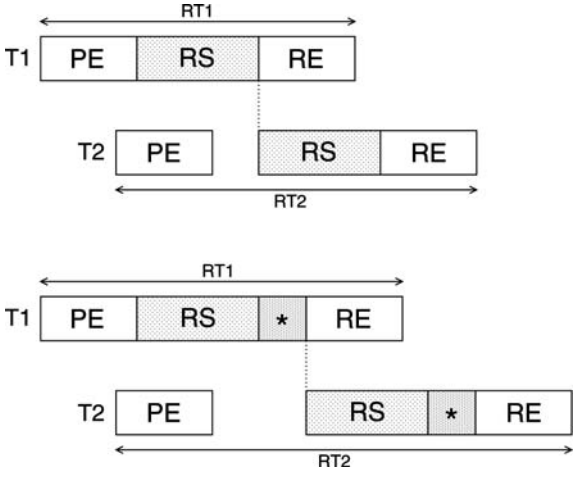

Fig. 1 Stage diagrams showing the interaction between mental operations in a PRP paradigm in conditions of high temporal overlap between tasks (i.e., at short SOAs), for both control participants (*upper two diagrams*) and CHI patients (*lower two diagrams*). In all diagrams, *PE* perceptual encoding, *RS* response selection, *RE* response initiation/execution. RT1 and RT2 are estimates of the time taken to respond to the first stimulus and the second stimulus, respectively. Effects of CHI are hypothesized to be reflected in the prolongation (*marked with asterisks*) of the time taken to carry out central operations, such as RS

The model proposed by Dell'Acqua and colleagues seems inconsistent with the view that CHI represents a control disorder, as proposed in the studies described in the foregoing paragraph. The model predicts that CHI patients should be consistently slower than controls as long as a speeded task entails response selection. Thus, choice-RT should be slower for CHI patients than controls even when a task is performed in isolation. A further prediction based on this model relates to the relative size of the CHI deficit when estimated under single-task and dual-task conditions: The CHI single-task deficit should equal the CHI increase in the magnitude of the PRP effect. By contrast, if CHI patients have a difficulty in coordinating or switching between performance of Task1 and Task2, this would naturally seem to predict an enhancement in the PRP effect as compared to the single-task slowing.

The purpose of the present work is to test these contrasting predictions. A group of CHI patients and a group of age-matched controls performed in a PRP paradigm and in a single-task paradigm. The single task was identical to Task2 of the PRP paradigm. To anticipate, the results of the PRP paradigm revealed a PRP effect in both populations, and showed that CHI patients exhibited a more pronounced PRP effect than controls. The results of the single-task paradigm indicated longer RT for CHI patients than controls.

So far, in discussing comparisons of CHI patients and controls in single-task versus dual-task performance, we have been referring to direct measures of mean response latency. Another potentially illuminating question focuses attention instead on effect sizes (Cohen, 1988), i.e., measures of the average separation between different groups relative to the variation of that same variable within a group. If dual-task performance provides a more sensitive measure of the dysfunction underlying CHI than does single-task performance, then one would expect to find a larger effect size for patient status (CHI vs. normal) for dual-task as compared to single-task performance. This would, of course, imply that dual-task measures might be of special utility as diagnostic measures, providing superior ability to separate patients from normals.

From a theoretical standpoint, this increased sensitivity would be predicted by any theory postulating (1) that CHI patients show a reduction in cognitive resources, and (2) that dual-task, but not single-task, performance requires more resources than the limited amount available in CHI patients. On such an account (often implicit in the clinical literature, e.g., Richer, Bédard, Lepage, & Chouinard, 1998), stressing the system by requiring more resource-demanding dual-task performance would reveal an otherwise undetectable shortage of resources.

On the other hand, according to the alternative bottleneck-type account described above (which postulates that CHI patients simply show a slowing in the central stages that are subject to "bottlenecking"), it would appear that the two groups should show the same degree of

overlap in measures of dual-task performance as they show in measures of single-task performance. Furthermore, the model based on the notion of central processing slowing as the cause of the CHI prominent deficit (i.e., general slowness) yields an additional set of predictions concerning the relationship between the CHI deficit under single-task and dual-task conditions. If the CHI deficit in those conditions reflects a common functional source (i.e., central slowing) then a significant positive correlation should be found across subjects when the effect size equivalent of the CHI deficit in single-task performance is regressed against the same individual's CHI deficit measured in dual-task conditions.

Experiment

Method

Participants

A group of ten CHI patients, and a group of ten uninjured controls participated in the experiments. Data concerning demographic and clinical features of the CHI patients are reported in Table 1.

The CHI group was selected from referrals at the Bolzano 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, not seeking financial compensation for the injury, not pursuing litigation, severe CHI with Glascow Coma Scale (GCS; Jennett & Bond, 1975; Jennett, Snoek, Bond & Brooks, 1981) were observed with scores between 3 and 8 at admission in the Neuropsychology Unit. The post-traumatic amnesia (PTA) was estimated using the GOAT scale (Levin & Grossman, 1979). PTA duration was assessed by interviewing patients and relatives. None of the patients suffered from a PTA shorter than 7 days. Patients with a history of previous head injury were excluded in order to rule out potential cumulative effects of the head trauma following successive insults (e.g., Gronwall & Whrightson, 1975). CHI patients and control participants with a history of alcoholism, psychiatric disorder, mental retardation, or neurological disease were also excluded. The reported neurological lesions were assessed through magnetic resonance imaging.

The selected patients underwent 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. Verbal functions were assessed by Phonemic and Categorical Verbal Fluency. All patients showed Equivalent Points (Spinnler & 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 concentrating, fatigue, irritability, and difficulty in performing tasks at the same level as they did before trauma.

The mean age of CHI patients were 31.5 years (SD = 8.6), and 10.9 years (SD = 2.5), respectively. The mean Glasgow Coma Scale score at hospital admission was 6.3 (SD = 1.4), and the mean coma duration was 11.8 days (SD = 7.6). All CHI patients were tested between 5 and 39 months after injury ($M = 16.4$, SD = 13.8). The control group was matched for sex, age ($M = 30.9$, SD = 8.1), and years of education ($M = 11.3$, SD = 2.8). Controls and CHI patients did not show significant differences in any of these variables (for age: $t(9) = 0.14$, $P > 0.9$; for education: $t(9) = -3$, $P > 0.7$). Controls and CHI patients of the same sex were paired randomly, trying to obtain in each pairing the closest match for age.

All the participants (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.

Visual stimuli

The visual stimuli were disks with a diameter of 1.7 degrees of visual angle, filled with blue color (CIE coordinates: $Y = 14.6$, $x = 0.266$, $y = 0.269$), or red

Table 1 Demographic and clinical features of CHIs

N	SEX	AGE (years)	EDU (years)	GCS	COMA (days)	Lendion	PTA (days)	Lesion-Test (months)
1	M	26	10	7	13	Frontal right	7	12
3	M	48	8	8	10	Diffuse axonal injury	8	32
4	M	17	9	8	10	Bilateral frontotemporal	30	6
5	M	34	10	4	4	Frontal right, parietal bilateral	50	6
6	M	31	16	8	5	Diffuse axonal injury	26	6
7	F	24	11	6	8	Temporoparietal right	7	5
8	M	34	8	6	7	Frontotemporal left	10	16
9	F	29	13	5	28	Diffuse axonal injury	28	36
10	M	40	13	5	22	Frontal right	36	39

N: arbitrary numbers assigned to CHI patients; *Sex*: *M*: male, *F*: female; *Educ.*: years of education; *GCS*: Glasgow Coma Scale scores (at admission in the rehabilitation unit); *PTA*: Post-traumatic amnesia (GOAT scores); *Lesion-test*: time-post-injury interval

color (CIE coordinates: $Y = 18.4$, $x = 0.357$, $y = 0.339$). The visual stimuli were displayed on the light gray background (Y = 22.2) of a SVGA computer screen (cathode ray tube) controlled by a 586 CPU.

Auditory stimuli

The auditory stimuli were pure tones, presented for 100 ms, with a frequency of 400 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).

General procedure

The single-task and dual-task conditions were administered at one week of distance. The order of conditions was counterbalanced across participants, such that half of the participants were first administered the single-task condition, and then the dual-task condition, whereas the opposite condition order was used for the other half of the participants. The response mapping adopted by each participant in the color task (see below) was constant across single-task and dual-task conditions. The experiment was carried out in a dimly lit, sound-attenuated room, at the constant presence of a research assistant who paced the trial presentation.

Dual-task procedure

On each trial of the experiment, an auditory stimulus (i.e., a pure tone) and a visual stimulus (i.e., a colored disk) were presented in succession, with each stimulus requiring a distinct speeded response. The tone was always presented as the first stimulus, followed by the colored disk as the second stimulus. Participants were instructed to respond to the stimuli in the order in which the stimuli were presented, that is, the response to the tone had always to be emitted before the response to the colored disk.

Each trial began with the presentation of a fixation cross at the center of the monitor. The research assistant initiated the trial by pressing one of the buttons of a mouse connected to the CPU. After the mouse-button press, the fixation cross disappeared, and a fixed blank interval of 600 ms elapsed before the presentation of the tone. Participants were instructed to make an immediate two-alternative forced choice response based on the tone pitch. Using a microphone placed in front of their mouth, at the distance of about 5 cm, participants had to say < high > if the pitch of the tone was high, or < low > if the pitch of the tone was low, while trying to avoid noise (e.g., cough) or hesitations (e.g., 'hum...'). At one of three possible SOAs (either 350, 900, or 1,550 ms) following the tone, the colored disk was displayed on the monitor. With 0.5 probability on each trial, the color of the disk could be either red or blue. Participants were instructed to make a two-alternative forced response based on the color of the displayed disk. The hand-color mapping was varied every two participants, with half of the participants pressing the 'Z' key when the disk was blue, and the 'M' key when the disk was red, and the other half of the participants responding with the opposite mapping. Participants were instructed to keep the index fingers of both their hands on the appropriate response-keys, and encouraged to perform both speeded tasks as fast and accurately as they could.

Two distinct sessions preceded the data recording session. In a first session, the microphone sensitivity was adjusted according to each participant's vocal characteristics. A sequence of 10 tones with frequencies of either 400 Hz or 1,200 Hz was presented to each participant. The participants were instructed to say, as fast and accurately as possible, < high > if the tone was high-pitched, or < low > if the tone was low-pitched. The sequence of tones was repeated until no failures in detecting the vocal response occurred. At each repetition of the tone series, the sensitivity threshold of the microphone was lowered of a factor scale of 2/30. The second session was dedicated to practice for the actual experiment. Participants performed two blocks of 24 trials each. At the end of the practice session, the instructions were repeated, and participants performed six blocks of 36 trials each. Levels of SOA, tone pitch, and color of the disk were fully randomized in each block of trials.

Single-task procedure

Each trial began with the presentation of a fixation cross at the center of the monitor. The research assistant initiated the trial by pressing one of the buttons of a mouse connected to the CPU. After the mouse-button press, the fixation cross disappeared, and a fixed blank interval of 600 ms elapsed before the presentation of the colored disk. Participants were instructed to make a two-alternative forced response based on the color of the displayed disk. The hand-color mapping was varied every two participants, with half of the participants pressing the 'Z' key when the disk was blue, and the 'M' key when the disk was red, and the other half of the participants responding with the opposite mapping. Participants were instructed to keep the index fingers of both their hands on the appropriate response-keys, and encouraged to perform the speeded task as fast and accurately as they could.

Before the data recording phase of the experiment, participants performed one block of 36 trials each. At the end of the practice session, the instructions were repeated, and participants performed six blocks of 36 trials each.

Results

The data from one patient (patient 2) and the data from the associated control subject were excluded from the following analyses because the patient completed only 1/3 of the session with dual-task trials. The analyses concentrated on correct RTs and on the proportion of correct responses collected from the remaining nine patients and nine control subjects. Outlier filtering was carried out by sorting correct RTs in each cell of the single-task and dual-task designs, and excluding temporarily from consideration the shortest and longest RTs. The mean (M) and standard deviation (σ) of the remaining RTs were then computed. Cutoff values were established using the following equations:

$$\text{Vlow} = M - C \times \sigma \quad (1)$$

$$\text{Vhigh} = M + C \times \sigma, \quad (2)$$

where C was a parameter that depends on sample size (see Van Selst & Jolicoeur, 1994), insuring that the final estimate of mean RT in each cell was not influenced by sample size. The shortest and longest RTs were then checked against the cutoff values, and treated as outliers if one or both of these data points were outside the bounds. If an outlier was found, then the algorithm was applied anew to the remaining data points. A summary of the results from both the single-task and the dual-task conditions is graphically reproduced in Fig. 2.

Single-task

Correct RTs and proportion of correct responses in the single-task condition were submitted to analysis of variance (ANOVA) considering population (CHI vs. controls) as a between-subject factor. The ANOVA on RT revealed a significant effect of population, $F(1,16) = 10.4$, MSe = 22,181, $P < 0.005$, with CHI patients producing generally slower RTs than controls (i.e., 589 ms vs. 363 ms, respectively). CHI patients were as accurate as controls in the single-task condition (0.97 vs. 0.97 proportion of correct responses, respectively; $F < 1$).

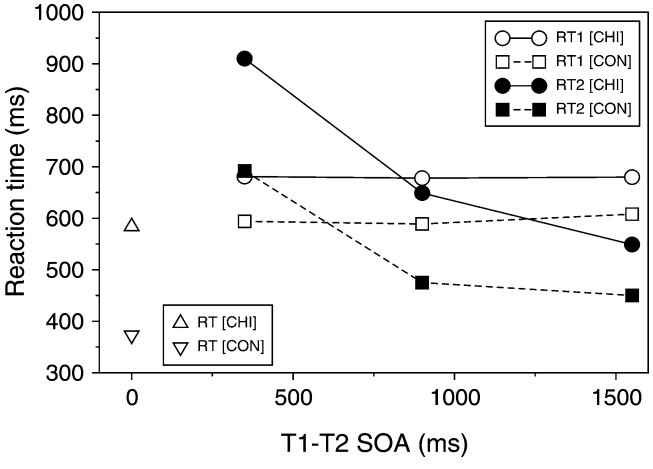

Fig. 2 Summary of the experimental results. Mean RT in the single-task condition (*triangular symbols*) and in the PRP condition (*circular* and *square symbols*). Inside the legend box, *CHI* CHI patients and *CON* controls

Dual-task

Correct RT1s, correct RT2s and proportion of correct responses in each task of the dual-task condition were submitted to separate ANOVAs, each considering population (CHI vs. controls) as a between-subject factor, and SOA as a within-subject factor. The ANOVA on RT1 indicated that CHI patients were slower than controls, F(1,16) = 5.2, MSe = 60,919, $P < 0.04$. No effect of SOA, or of the interaction between population and SOA emerged as significant in this analysis, all Fs < 1. The ANOVA on the proportion of correct responses in Task1 did not reveal any significant factor effect, all Fs < 1. On an average, the proportion of correct responses of the CHI patients was 0.97, and the proportion of correct responses of the controls was 0.98.

The ANOVA on RT2 revealed a significant effect of population, $F(1,16) = 10.1$, MSe = 65,978, $P < 0.006$, a significant effect of SOA, $F(2,32) = 67.3$, MSe = 7,739, $P < 0.001$. The RT2 difference between CHI and controls increased from 100 ms to 218 ms as SOA decreased, and this produced a significant interaction between population and SOA, $F(2,32) = 3.3$, MSe = 7,739, $P < 0.05$. The ANOVA on the proportion of correct responses in Task2 indicated a marginal effect of SOA, F(2,32) = 3.0, MSe = 0.001, $P < 0.07$, with the proportion of correct responses decreasing from 0.96 to 0.94 as SOA was reduced. No other factor or interaction emerged as significant in this analysis, all Fs < 1. The present set of results sets the first step towards demonstrating a common cause of single-task and dual-task costs in CHI patients, insofar as CHI effects were detected—as predicted in the model reproduced in Fig. 1—in both single-task RTs and dual-task RTs. Further analyses were however needed for a direct quantification of CHI effects across the different dependent variables selected for the present experiment and, more importantly, for a direct cross-task comparison that ought to reveal whether CHI effects under dual-task condition are disproportionate compared to CHI effects single-task conditions as several researchers in this area of neuropsychological studies had previously maintained (see Introduction). The results of these further analyses are reported in the next section.

Effect size (Cohen's d)

The comparison between CHI effect on single-task performance and dual-task performance was carried out through the transformation of the absolute CHI versus

controls RT differences into Cohen's ds. These data are reported in the three panels of Table 2.

In the top panel, the single-task RT of the CHI patients is reported in column 1, the single-task RT of the controls is reported in column 2, the difference between these RT parameters is reported column 3, and the associated Cohen's d is reported in column 4. Cohen's ds were calculated using the following equation (see Cohen, 1988):

$$\frac{RT_{RT\text{chi}-RT\text{con}}}{\sqrt{(\sigma^2_{RT\text{chi}} + \sigma^2_{RT\text{con}})/2}}. \quad (3)$$

Cohen's ds were corrected for reliability using an adaptation of the formula proposed by Hunter and Schmidt (1990). Separate parameters of reliability for CHI patients' RT and controls' RT were calculated by considering, for each participant, the mean RT of odd trials and the mean RT of even trials. The correlation between odd-trial mean RT and even-trial mean RT was computed independently for CHI patients and controls. Corrected Cohen's ds were generated by dividing the Cohen's ds by the square root of the result of the following equation:

$$\sqrt{\frac{\text{Cov}(RT_{\text{chi(odd)}}, RT_{\text{chi(even)}})}{\sigma_{RT\text{chi(odd)}} \times \sigma_{RT\text{chi(even)}}} \times \frac{Cov(RT_{\text{con(odd)}}, RT_{\text{con(even)}})}{\sigma_{RT\text{con(odd)}} \times \sigma_{RT\text{con(even)}}}}. \quad (4)$$

The data from the dual-task condition are reported in the middle panel (RT2) and the bottom panel (RT1) of Table 2, where the PRP effect (mean RT2 at the shortest SOA – mean RT2 at the longest SOA) for the CHI patients and for the controls are reported in column 1 and column 2, respectively. The difference between these parameters is reported in column 3. Cohen's ds were calculated using the formula:

Table 2 Mean RTs of CHI patients (CHI) and controls (CON) across the steps of the algorithm used for CHI effect size estimation (i.e., transformation into Cohen's d). (See the text for details)

Single-task RT				
RT_{chi}	RT_{con}	$RT_{RTchi - RTcon}$	Cohen's d	Corrected d
335.72	465.36	−129.64	−0.87	−0.88
721.77	370.54	351.23	2.36	2.38
479.68	346.74	132.95	0.89	0.90
926.81	355.32	571.49	3.84	3.87
381.23	432.73	−51.49	−0.35	−0.35
432.59	350.28	82.31	0.55	0.56
580.68	291.00	289.68	1.95	1.96
858.88	411.37	447.51	3.01	3.03
542.07	335.98	206.09	1.39	1.39
			Mean	
			1.43	1.42
Dual-task RT2				
PRP_{chi}	PRP_{con}	$PRP_{PRPchi - PRPcon}$	Cohen's d	Corrected d
131.35	195.40	−64.06	−0.39	−0.41
104.01	189.98	−85.97	−0.52	−0.55
244.85	254.13	−9.28	−0.06	−0.06
496.18	72.91	423.27	2.56	2.69
244.94	427.80	−182.87	−1.10	−1.16
573.39	395.75	177.64	1.07	1.13
423.99	132.89	291.10	1.76	1.85
513.93	319.57	194.36	1.17	1.24
532.42	245.85	286.57	1.73	1.82
			Mean	
			0.69	0.73
Dual-task RT1				
$RT1_{chi}$	$RT1_{con}$	$RT1_{RT1chi - RT1con}$	Cohen's d	Corrected d
489.32	612.66	−123.34	−0.84	−0.85
584.53	627.44	−42.91	−0.29	−0.29
668.12	564.99	103.13	0.70	0.71
912.27	421.19	491.09	3.34	3.37
624.82	820.92	−196.10	−1.34	−1.35
772.33	562.80	209.53	1.43	1.44
758.50	486.35	272.15	1.85	1.87
695.50	658.15	37.35	0.25	0.26
608.24	628.23	−20.00	−0.14	−0.14
			Mean	
			0.56	0.55

$$\frac{PRP_{\mathrm{PRPchi}} - \mathrm{PRPcon}}{\sqrt{(\sigma^2_{\mathrm{PRPchi}} + \sigma^2_{\mathrm{PRPcon}})/2}}. \quad (5)$$

Reliability-corrected Cohen's ds were generated by dividing the Cohen's ds by the square root of the result of Eq. 4. The mean correlation between odd and even trials in the longest and shortest SOA conditions was used as the correlation coefficient included in Eq. 4. Mean Cohen's d tended to be greater in the single-task condition than in any of the other dual-task conditions. Separate t-tests were conducted to compare the Cohen's ds associated with RT2 and RT1 performance ($t(8) = -0.18$, $P > 0.8$), with RT2 and single-task performance ($t(8) = -1.6$, $p > 0.12$), and with single-task and RT1 performance ($t(8) = -2.1$, $p < .07$), showing either no significant difference between the variables considered, or a marginally significant trend (involving single-task and RT1 performance). This trend was, however, opposite in direction to what would be predicted by models postulating that CHI effects under dual-tasking reflect a disorder of executive control in addition to simple slowing of central processing (see Introduction). This striking finding poses also interesting questions about a possible interpretation of this opposite effect, that the present study is not able to solve. More power is indeed needed to understand how reliable (or randomly fluctuating) this effect would be in the context of a study necessarily involving more patients and normal participants.

A Spearman analysis of the correlation between reliability-corrected Cohen's ds across the different conditions of the present experimental paradigm provided support for the second set of predictions derived from the model reported in Fig. 1. The results of the correlation analysis are reported in Table 3.

Apart from an expected positive correlation between RT1and RT2, which is generally consistent with bottleneck models of the PRP effect (see Pashler, 1994), it is important to note in Table 3 the significant correlations between the CHI effect in the single-task condition and the CHI effect in each subtask of the dual-task condition, each accounting for a not negligible proportion of the variance (about 0.44) associated with the Cohen's ds distribution. The present set of results sets the second step towards demonstrating a common cause of single-task and dual-task costs in CHI patients, insofar as CHI effects under single-task conditions were no smaller (actually, slightly greater) than CHI effects detected under dual-task conditions. To reiterate a concept put forth in the Introduction and anticipate the more detailed discussion offered in the forthcoming paragraphs, what seems a safe conclusion based on these findings is that no support has been found in the present empirical context for a putative functional independence of the cause of CHI effects under single- and dual-task conditions. Quite in contrast, the set of significant correlations reported above across each two out of the three conditions implemented in the present design (i.e., single-task, Task1 in dual-task, Task2 in dual-task) reinforce our initial hypothesis of a unique cause of CHI most typical behavioral manifestation, namely, central processing slowing as the cause of impaired speeded performance in these patients.

Table 3 Correlation matrix of Cohen's d translations of CHI effects in the different conditions of the present design (*SRT*: single-task condition; *RT1*: dual-task condition, Task 1; *RT2*: dual-task condition, Task 2)

	SRT	RT1
SRT		
RT1	0.66* ($R^2 = 0.44$)	
RT2	0.66* ($R^2 = 0.43$)	0.72* ($R^2 = 0.52$)

The values reported in the table are Pearson rs coefficients (R^2 in parentheses). Asterisks mark values of r associated with $P = 0.05$ or less

Summary and discussion

By employing different experimental techniques, a number of neuropsychological studies (many reviewed in Ferraro, 1996) have sought to explain the reduction in the speed at which CHI patients perform a variety of cognitive tasks. The results of the present experiment, that involved a direct comparison between CHI patients and a group of age-matched controls performing in a single-task paradigm and in a dual-task (PRP) paradigm, were clear-cut in supporting a prior explanation that we had advanced for this general slowness and that was discussed in the Introduction to the present work. CHI patients were generally slower (but not less accurate) than controls in both single-task and PRP conditions. First, this finding questions interpretations of CHI as a neurological disorder whose behavioral reflections are restricted to multi-tasking situations (e.g., Leclercq et al., 2000), or interpretations of the disorder as a specific problem with executive control (e.g., Park et al., 1999; Richer et al., 1998). Secondly, a fine-grained analysis of the costs associated with the CHI disorder in the present experiment is consistent with the view that the constellation of CHI symptoms may be attributable solely to slowing of central processing, as suggested by Dell'Acqua et al. (2001; 2003; see Fig. 1). As found in these previous studies, the PRP effect exhibited by CHI patients was indeed larger than the PRP effect reported by controls. However, the more refined analyses (i.e., Cohen's *d* transformation of CHIs' and controls' performance estimates and the correction for the relative reliability of such estimates) showed that the CHI increase in PRP effect was (1) not significantly different from the CHI effect found under single-task conditions, and (2) slightly different from the CHI effect reflected in the lengthening of RT1 in the PRP paradigm, but in a way that was incompatible with the view derived from models of CHI as a control disorder. Indeed, there was a marginally significant tendency of the CHI effect

estimates to be slightly greater, and not smaller as the hypothesis of CHI as a control disorder suggests, in single-task conditions than in dual-task conditions. Furthermore, there were clear signs of a strict relationship of CHI effects across the different conditions tested in the present experimental scenario. As predicted on the hypothesis of a common source of CHI effects under single-task and dual-task conditions, Cohen's *d* estimates of CHI effects in the single-task condition were correlated with Cohen's *d* estimates of CHI effects in each of the subtasks in the dual-task condition. Given these findings, it would seem that CHI interpretations that assume multi-task costs are disproportionately large (i.e., larger than costs predictable on the basis of CHI performance under single-task conditions) in these individuals need to be reconsidered.

A CHI interpretation that shares a number of analogies with the one proposed herein has recently been advanced by Hein, Schubert, and Von Cramon (2005). These authors used a standard PRP paradigm in which auditory stimuli and visual stimuli were presented in succession. A manipulation held to affect a precentral stage of processing was implemented in this paradigm by varying systematically the contrast of the visual stimuli against the background, and producing conditions in which the visual stimuli were 'easy' to detect (when the contrast was high) or 'difficult' to detect (when the contrast was low). As expected, based on several PRP studies on the interaction of this type of perceptual manipulations with the SOA manipulation (e.g., McCann & Johnston, 1992; Pashler & Johnston, 1989), controls' RT2, beside showing the ubiquitous PRP effect, was affected by the contrast manipulation (i.e., longer RT2 to low-contrast vs. high-contrast stimuli) only at long SOA. At short SOA, RT2 to high-contrast stimuli and RT2 to low-contrast stimuli were identical. CHI patients also reported a PRP effect under these conditions, which was magnified compared to the controls' PRP effect. However, the contrast effect for the CHI patients, that was analogous to that of controls' at long SOA, was reversed (i.e., shorter RT2 to low-contrast vs. high-contrast stimuli) at short SOA. Interestingly, the reversed contrast effect was not replicated when a group of patients affected by Parkinson was tested under comparable experimental conditions. The increased PRP effect led Hein et al. (2005) to interpret CHI as prolonging central processing for response selection. The reversed contrast effect was taken to reflect a potential additional impairment in CHI patients, in the form of an interplay between the processing of the auditory stimulus and the processing of the visual stimulus, whose abrupt onset, when the visual stimulus was particularly salient, captured attention at the expenses of first stimulus processing. We note the general structure of the model proposed by Hein et al. (2005) fits well with the results reported here. In terms of predicted results in a PRP paradigm, however, the proposal that a CHI extends its influence to pre-bottleneck stages of processing, in addition to central processing stages, makes the Hein et al.'s model undistinguishable from the model proposed by Dell'Acqua and coworkers. Certainly the reversed contrast effect poses interesting questions about the exact nature of CHI, which future experimental investigations may be able to answer. What is critical for the present argument is that, with the Hein et al.'s model, further support is provided for the hypothesis that a unitary cause may underlie both single-task costs and multi-tasking costs in CHI patients, as we have suggested in earlier work. Furthermore, Hein et al.'s model is consistent with Dell'Acqua et al's proposal in attributing a substantial portion of such costs to central processing slowing.

Where the results of the present study and Hein's et al. study seem less directly comparable is with respect to the relationship between CHI effects under single-task conditions and CHI effects under dual-task conditions. As argued in the Introduction, if CHI is characterized only by central processing slowness (or, more specifically, response selection slowness), then one can predict an obvious relationship between the results obtained under single-task conditions and those obtained under dual-task conditions. With the proviso that the metric used to generate an estimate of CHI deficits equate the selected dependent variable under each condition (in the present case, reaction time) for reliability, estimates of the CHI deficit under single-task condition should correlate positively with estimates of the CHI deficit obtained from each subtask under dual-task conditions. In fact, the correlation analysis carried out in the present experimental context confirmed this, reinforcing, therefore, the view that the cause of CHI slowness is independent of the exact nature of the speeded task employed to test CHI effects. Unfortunately, an equivalent analysis comparing CHI effects across single-task and dual-task conditions was not carried out by Hein and colleagues, thus leaving this empirical aspect of their work—and a potential cross-study comparison focusing on this specific aspect—unresolved. Of note, the present finding of a significant positive correlation between Cohen's *d* estimates of CHI effects in the single-task condition and in each subtask included in the dual-task condition also helps rule out a potential problem with the results of the present study, that is tied to the fact the single-task condition of the present study was devised by isolating Task 2, but not Task 1, of the dual-task condition. In this respect, one might argue that the quantification of CHI effects under the single-task condition was somewhat artificial, or at least amenable to substantial variations depending on the nature of the task chosen to estimate CHI effects. In the present scenario, however, the separate correlations found between single-task CHI effects and CHI effects in each subtask of the dual-task condition appear to be more in line with our interpretation of the cause of CHI slowness than the view briefly described above. If the quantification of CHI effects had depended on whether Task 1 or Task 2 were chosen as single-task, our intuition is that a positive correlation would have been found only (or, alterna-

tively, would have been more salient) between CHI effects detected using analogous tasks, a pattern that is not supported by the results reported in Table 3.

The finding of a selective impairment of CHI on central resource allocation has many important implications also for CHI rehabilitation. Limitations in central processing capacity can influence performance on a variety of task and daily living situations. Specific rehabilitation settings may be developed based on recent findings showing drastically reduced PRP effects through extended practice (e.g., Ruthruff, Van Selst, & Johnston, 2005).

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