Electrophysiological correlates of spatial processing during multitasking

Zaira Romeo[a], Mario Bonato[b], Marco Zorzi[a,b], Chiara Spironelli[b,*]

[a] *IRCCS San Camillo Hospital, Venice, Italy*
[b] *Department of General Psychology and Padova Neuroscience Center, University of Padova, Italy*

ARTICLE INFO

ABSTRACT

Multitasking is ubiquitous in everyday life. It can have a detrimental effect on several cognitive abilities including spatial processing in both brain-damaged and healthy participants. The present study investigated, in healthy adults, the electrophysiological mechanisms associated with correct detection vs. misdetection of peripheral visual target(s) while processing concurrent visual or auditory stimuli. Correct responses were coupled with increased N1 amplitude under visual (i.e., intra-modal) load but not under auditory (i.e., cross-modal) load. Under visual load, error responses were associated to opposite patterns on N1/N2 components for unilateral and bilateral stimuli. In particular, errors were marked by significantly reduced N1 and N2 amplitude for the left and right visual field, respectively, whereas higher N1 amplitude was found for errors to bilateral targets. This suggests that early negative components represent the biological marker of target awareness under visual load, whereby correct target detection is grounded on a threshold criterion. These results provide an electrophysiological correlate for the allocation of capacity-limited cognitive resources during the concurrent processing of multiple and heterogeneous visual stimuli.

1. Introduction

In everyday life we continuously process the space around us to detect behaviorally-relevant information. Spatial processing is performed in virtually all everyday contexts, frequently in concurrence with other tasks (Nijboer et al., 2016; Schaefer, 2014). The ubiquitous performance decline under multitasking is often explained in terms of a limited amount of depletable resources which are deployed across tasks (Marois and Ivanoff, 2005). However, other explanations emphasize "structural" limits in performing two or more processes in parallel (Koch et al., 2018). Furthermore, from a neurofunctional perspective the correlates of multitasking (Al-Hashimi et al., 2015) are very closely associated with the cognitive characteristics of the specific task at hand (Sasai et al., 2016), with limited generalizability to the dual-tasking process *per se*.

The present study focuses on the effect of multitasking on spatial monitoring – as revealed by electrophysiological measures. Besides the generalized slowing of responses, many studies have observed that increasing load induces subtle spatial processing asymmetries. The direction of these spatial asymmetries is however controversial. On the one hand, there is converging evidence that processing of peripheral stimuli is better in the right than in the left hemispace both under unimodal and multimodal load (Chen and Spence, 2017). On the other

hand, some studies have reported an advantage for stimuli in the left visual field when left and right hemispaces have to be simultaneously attended (Holländer et al., 2005; Verleger et al., 2010; Verleger and Śmigasiewicz, 2015). The very influential load theory of visual attention (Lavie, 1995, 2005) explains in general how the interference of peripheral visual distracters changes as a function of the amount of processing resources available but it does not speak to the issue of how the processing of behaviorally-relevant targets is influenced by concurrent task demands.

Multitasking impacts spatial processing more dramatically in clinical populations who have suffered cognitive/neural impairment (Bonato, 2012). A striking example is the boost of omission rates for contralesional visual targets in stroke patients when asked to perform a concurrent task– whether visual or auditory (Bonato et al., 2010, 2012, Bonato et al., 2013). In healthy participants the impact of concurrent tasks is much more limited, yet it can be highlighted by an implicit measure such as pupil dilation (Lisi et al., 2015). The pupillometry results of Lisi et al. (2015) showed that the effect of multitasking reflects intrinsic task demands rather than the mere amount of information to be kept in working memory. A complementary approach for investigating the effect of multitasking on spatial processing is to assess how its electrophysiological correlates change as a function of load. Studies on healthy participants have shown that increasing attentional

* Corresponding author. Department of General Psychology, University of Padova via Venezia 8, 35131, Padova, Italy.
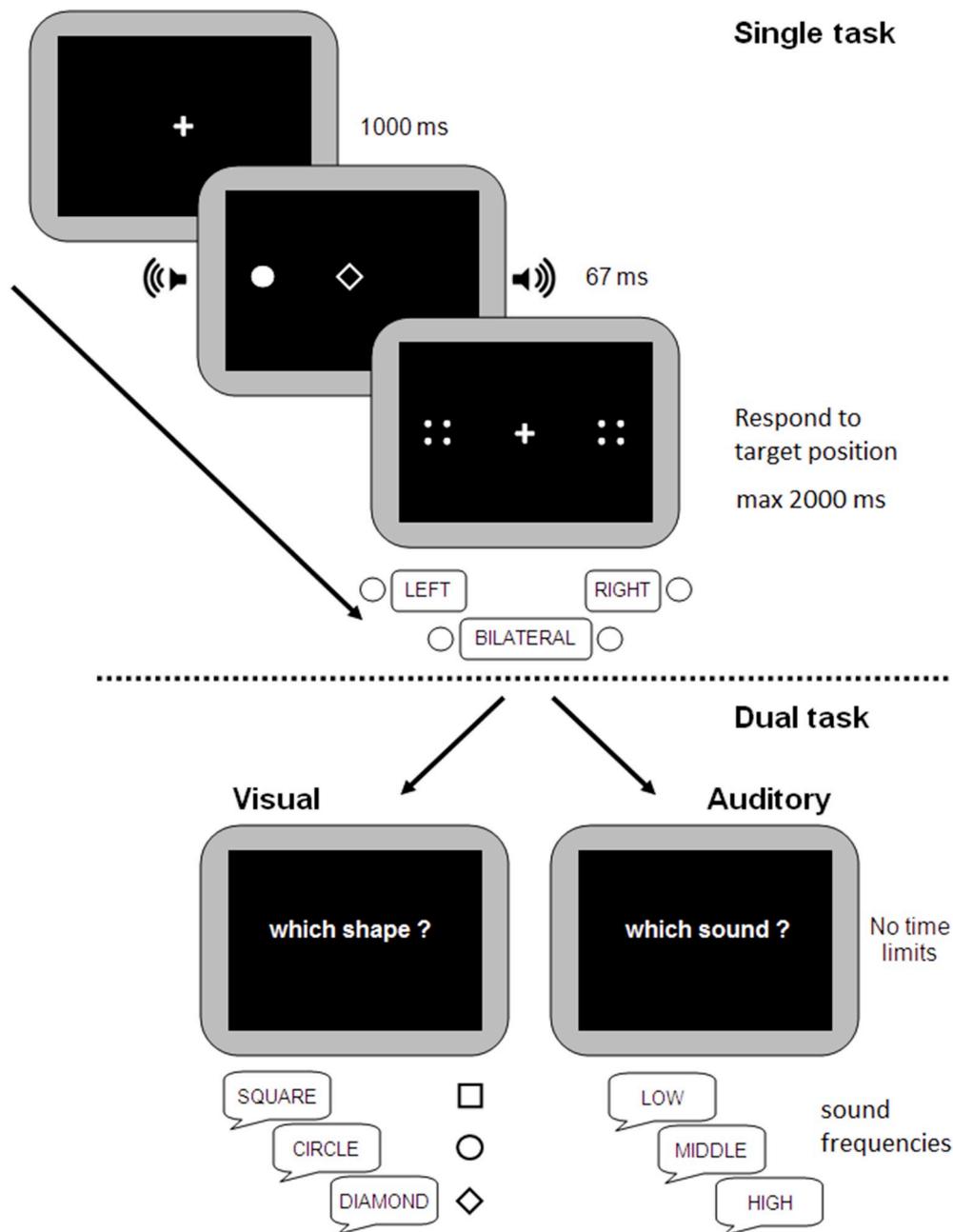*E-mail address:* chiara.spironelli@unipd.it (C. Spironelli).

Fig. 1. Trial structure (not in scale) of the Single task (top panel) and of Dual tasks (bottom panel). Across all tasks the same stimuli were presented: lateralized dot(s), a central form and a binaurally presented sound, followed by two four-dot-die masks on left and right lateralized dot(s) position. In the Single task participants only had to report the position of the dot. In Dual tasks after the response to dot(s) position, participants had to report the identity of the central shape (Visual Dual-task: left side, bottom panel) or the pitch of the sound (Auditory Dual-task: right side, bottom panel).

load modulates the amplitude of the ERP components both at early (Bonato et al., 2015; Handy et al., 2001; O'Connell et al., 2011; Rorden et al., 2008) and late stages of visuo-spatial processing (Ding et al., 2014; Fu et al., 2008). In a previous study (Bonato et al., 2015), we observed a modulation of the P1 component and a concurrent deactivation of the primary visual areas during multitasking (though later components were also affected). However, it is important to emphasize that previous studies focused on the electrophysiological correlates of successful processing of targets. What happens in a healthy brain when stimulus processing leads to incorrect responses is much less known: to the best of our knowledge, no electrophysiological studies have investigated the mechanisms associated with the modulation of target awareness elicited by a purely top-down/multitasking manipulation that keeps stimuli constant across tasks. The present study was designed

to fill this gap.

We tested young healthy adults using a new version of the multi-tasking paradigm previously validated with supra-threshold visual stimuli (e.g., Bonato et al., 2015). We used brief stimulus duration (identical for all participants and determined through a preliminary calibration procedure) and bilateral visual masking to induce errors in the detection of the lateralized visual target(s) – in the attempt to mimic the impaired performance of brain-damaged patients. Our first aim was replicating the finding that early ERP components associated with correct target detection are modulated by multitasking. The amplitude of early ERP components is known to be modulated by factors like attentional processing, visual discrimination, and arousal (Hillyard et al., 1998; Vogel and Luck, 2000). It is therefore important to assess how these components are influenced by a multitasking context requiring

the parallel processing of several heterogeneous stimuli. We hypothesized that the amount of cognitive resources deployed to visuospatial processing of the lateralized targets (primary task) is affected by the concurrent processing of other stimuli when the latter become relevant through the manipulation of task instructions (i.e., single task vs multitasking), thereby modulating early visual ERPs. However, it is important to distinguish between concurrent processing of stimuli within the same sensory channel (i.e., visual, hereafter intra-modal load) and that arising from stimuli presented through a different sensory modality (i.e., auditory, hereafter cross-modal load). Though behavioral evidence in stroke patients suggests that intra- and cross-modal load induce a similar degree of impairment for contralesional visuospatial processing (e.g., Blini et al., 2016; Bonato et al., 2012), based on our previous ERP study we expected a stronger modulation of early ERP components for intra-modal load compared to cross-modal load (Bonato et al., 2015). We also expected a modulation induced by the different target position conditions (left, right, bilateral), which would also rule out any potential confounding effect of visual masking (which was bilateral and identical across conditions).

The second and crucial aim was to contrast the electrophysiological correlates of correct vs. incorrect responses to assess when and how processing of the visual targets turns into different behavioral responses. In this respect, we considered two possible patterns of results: (a) the ERP components related to correct vs. incorrect responses are similar but differ in amplitude, thereby highlighting that visuo-spatial processing in the two condition is qualitatively identical; (b) ERP patterns diverge at a given time-point, thereby marking a qualitative difference between target processing leading to correct vs. incorrect responses.

2. Materials and methods

2.1. Participants

Twenty undergraduates (8 males; mean age: 23.68 years) took part in the study. They were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971, average score > 96%) and had normal or corrected-to-normal vision. All participants gave their written informed consent to take part in the experiment, according to the Declaration of Helsinki. The experimental procedure was approved by the Ethics Committee of the Department of General Psychology, University of Padova.

2.2. Stimuli, tasks, and procedure

Participants sat at a distance of about 60 cm from a 38 × 30.5 cm computer monitor. The task was programmed and administered using E-Prime (Psychology Software Tools, Pennsylvania, USA, http://www.pstnet.com). Stimuli and procedure differed from the task used in Bonato et al. (2015) with respect to three important characteristics: i) targets were masked; ii) target duration was determined by means of a calibration procedure (carried out in a preliminary separate session); iii) response mapping was more straightforward.

The experimental paradigm is depicted in Fig. 1. Each trial started with a black screen (1000 ms) (note that a black background was present through the whole experiment), followed by a centrally-presented white fixation cross that lasted for 1000 ms. Then, a white dot target (approximately 0.8° of visual angle) appeared for 67 ms on the left side, on the right side, or bilaterally, at a lateral distance of about 16° of visual angle from the screen center. Therefore, either a single target (left-sided or right-sided) or bilateral targets (left- and right-sided) were presented. The three target position conditions were equiprobable.

There were three experimental tasks (Fig. 1): one single-task condition and two dual-task conditions (visual vs. auditory). Synchronously with the lateral target(s), a geometric shape (square, circle, or diamond, in equal proportion, about 1.1° of visual angle) was presented

at fixation and a pure tone (high frequency ≈ 800 Hz, medium ≈ 450 Hz, or low ≈ 255 Hz, in equal proportion) was binaurally presented by means of earphones. After the offset of sound (100 ms), two masks, made by four white dots (arranged like the face of a die), were presented bilaterally.

In the Single task, participants had to report the position of the target(s) (i.e., "right", "left", or "both" sides), while ignoring the central shape and the auditory tone. Participants were required to respond as fast and as accurately as possible by pressing a button on a standard qwerty keyboard (left index (d key) for left target, right index (k key) for right target). In case of bilateral targets they had to press both buttons at the same time. Absence of response before the end of the trial (2 s) was considered as an omission. In both Dual tasks, the display and the sequence of events were identical to that of the Single task. In the Visual Dual task, after having responded (by button press) to the position of the lateral visual target(s), participants had to verbally classify the centrally presented shape. In the Auditory Dual task, participants responded to the position of the lateral visual target(s) and then verbally classified the sound pitch as high, medium or low. The experimenter coded participants' oral responses to the identity of the centrally presented shape (in the Visual Dual task) or to the sound pitch (in the Auditory Dual task) by pressing the key corresponding to participants' response on a second standard qwerty keyboard, connected with the computer used for administering stimuli. There were no time limits to respond to the secondary tasks.

Each task comprised 162 trials, equally distributed in three blocks (3 repetitions x 3 sounds × 3 shapes x 3 spatial positions), for each task. Participants performed the Single task first, and then the Dual tasks (Visual vs. Auditory) in a counterbalanced order. The importance of maintaining gaze at fixation was stressed before each block.

The duration of the lateralized targets was determined by a calibration procedure (36 trials) implemented in a separate session, carried out two weeks before the ERP experimental task. In the calibration phase, stimuli and response modality were the same of the experimental task, while the duration of the targets was determined based on participants' accuracy to bilateral targets. A correct response led to a decreased presentation time (minus one refresh period) in the following trials. Errors led to increased presentation time (plus three refresh periods). Also response omission led to increased presentation time (plus two refresh periods) for the subsequent trials. The average duration for the last 24 trials of the procedure was taken as final outcome. The aim of this procedure was to determine an average duration that would have resulted in a relatively high number of errors and, at the same time, to use the same timing of events for all participants. This was the best and possibly the only methodological option allowing to then perform stimulus-locked ERP analyses. Target presentation time for the experimental task was then determined by subtracting one standard deviation from the mean target duration (measured by the number of refresh periods).

2.3. Data acquisition and analysis

EEG cortical activity was recorded by 32 tin electrodes, 30 mounted on an elastic cap (ElectroCap) according to the International 10–20 system (Oostenveld and Praamstra, 2001), and the other two applied on mastoids (M1, M2). Electro-oculogram, allowing the detection of eye movements, was recorded with a bipolar montage using two additional electrodes placed below the right eye (Io1) and on the left canthium (F9), respectively. All cortical sites were on-line referred to M1. Data were stored using the Micromed software (System Plus, Micromed, Mogliano Veneto, Italy). Data were recorded with a 0.2–30 Hz bandwidth; the sampling rate was set at 512 Hz and the impedance was kept below 5 kΩ.

EEG was continuously recorded in the AC mode. Data were off-line re-referenced to the average reference (including the activity of both mastoids). Signal analyses were carried out using the Brain Vision

Analyzer system (Brain Products GmbH, Germany). Eye movement artifact components (i.e., vertical and horizontal movements, and blinking) were corrected by applying the Independent Component Analysis (ICA) transformation to the EEG signal. Raw data were therefore segmented in epochs of 1.5-s intervals, including 0.5 s before and 1 s after target onset, and a 100-ms baseline preceding target onset was subtracted from the whole trial epoch. Trials in which participants made errors to the secondary task (form/sound discrimination) were a priori discarded (see the "Behavioral results" section) to ensure that the ERP analysis was conditioned on compliance to the dual task requirement (i.e., attending to the discrimination task). Trials with errors in the target detection task were excluded from the main analysis, but were included in the subsequent error analysis. Each trial was then visually inspected for any residual artifacts (e.g., head movements or muscular activity). Artifact-free trials (on average 92.25% and 82.64% for the main analysis and the error analysis, respectively, with no differences between conditions) were averaged.

The ERP analysis on errors was carried out on a sub-sample of participants who showed a sufficient number of target detection errors in the behavioral performance (see "Comparison of ERP components for correct vs. error responses to target position" in the result section).

On the basis of Global Field Power analysis and after visual inspection of grand-mean waveforms (Figs. 2 and 6), we analyzed the time-windows centered on P1, N1 and N2 peaks (i.e., 100–111 ms, 176–195 ms and 281–300 ms, respectively). The Kolmogorov-Smirnov test was applied to ensure that every ERP component was normally distributed (all ds ≤ 0.308, ps > 0.20). For statistical analysis, electrodes were clustered into two posterior quadrants/regions of interest: Left Hemisphere (LH: TP7, P7, O1), Right Hemisphere (RH: TP8, P8, O2). Thus, the mean amplitude values of the ERP measured in cortical sites with the same polarity were averaged.

3. Results

Both behavioral and ERP data were analyzed using repeated measures analysis of variance (ANOVA). The Greenhouse-Geisser (GG) correction was applied in the case of violation of sphericity (in these cases, we report uncorrected degrees of freedom, epsilon values, and corrected probability levels). Post-hoc comparisons were computed using the Newman-Keuls test (p < 0.05).

All analyses have been carried out using the Statistica software (Statsoft Italy, 6.1 version). Only significant main effects or interactions are reported.

3.1. Behavioral results

Performance in the secondary task was high: mean accuracy was 95.7% in the Visual dual task (range 89–100%) and 88.9% in the Auditory dual task (range 74–98%). Trials with errors in the secondary task (shape/sound discrimination) were discarded for the analyses of the spatial monitoring task.

Accuracy in the spatial monitoring task was analyzed by means of a two-way ANOVA with Load (three levels: Single vs. Visual Dual vs. Auditory Dual) and Target Position (three levels: Left Visual Field [LVF] vs. Bilateral vs. Right Visual Field [RVF]) as within-subjects factors. The main effect of Load was significant (F(2,38) = 10.67, p < 0.001, GG ε = 0.80). Accuracy was lower in the Visual Dual Task (57%) compared to both Single Task (67%) and Auditory Dual Task (66%) (all ps < 0.001). In addition, accuracy was significantly higher for LVF (74%) compared to bilateral (54%, p < 0.05) but not RVF (62%) targets (Target Position main effect (F(2,38) = 3.81, p < 0.05, GG ε = 0.83). A significant two-way interaction (F(4,76) = 3.29, p < 0.05, GG ε = 0.68) revealed that accuracy was higher for LVF compared to bilateral targets in all tasks (all ps < 0.05), whereas accuracy for RVF compared to bilateral targets was higher in the Single Task condition only (p < 0.001).

The same analysis was carried out on correct target detection reaction times. There was a main effect of load F(2,38) = 23.64, p < 0.001, GG ε = 0.91), with faster RTs in the Single task (551 ms) compared with both Dual task conditions (Visual: 726 ms, Auditory: 667 ms; all ps < 0.001). A main effect of Target Position was also found (F(2,38) = 3.57, p < 0.05, GG ε = 0.72), RTs being faster for LVF (618 ms) compared with bilateral (676 ms, p < 0.05), but not RVF (652 ms) targets.

3.2. ERP results

3.2.1. Analyses of ERP components of correct target detection

As a first step, we analyzed the results of the whole sample (20 participants). This analysis included the correct responses only. We performed separate three-way ANOVAs on P1, N1 and N2 time-intervals (Fig. 2) with the following factors: Load (three levels: Single vs. Dual Visual vs. Dual Auditory), Target Position (three levels: LVF vs. Bilateral vs. RVF) and Hemisphere (two levels: Left vs. Right).

3.3. P1 component

The ANOVA carried out in the early time interval corresponding to the P1 component (100–111 ms after target onset) revealed a Load by Target Position interaction (F(4,76) = 2.71, p < 0.05, GG ε = 0.77). However, post hoc analysis did not reveal significant differences among conditions. The significant interaction Target Position by Hemisphere (F(2,38) = 5.12, p < 0.01, GG ε = 0.85) indexed that LVF targets elicited greater right than left hemisphere positivity (p < 0.001), whereas bilateral and RVF targets evoked similar, bilateral, activation (Fig. 3).

When considering within-hemispheres differences, greater positivity was measured in the left hemisphere for bilateral than for LVF targets (p < 0.01). No other main effect or interaction was significant.

3.4. N1 component

The ANOVA carried out in the time interval corresponding to the N1 component (176–195 ms after target onset) showed a main effect of Load (F(2,38) = 4.07, p < 0.05, GG ε = 0.78). We found a greater negativity under the Visual Dual Task (−3.10 μV) than under the Single task (−2.04 μV, p < 0.05), whereas no differences were found considering the Auditory Dual task (−2.48 μV). The ANOVA also revealed a significant Target Position by Hemisphere interaction (F(2,38) = 4.13, p < 0.05, GG ε = 0.85), with increased amplitude for LVF and bilateral targets in the left vs. right hemisphere (p < 0.001 and p < 0.05, respectively), and a bilateral pattern of activation for RVF targets (Fig. 4).

When considering within-hemispheres differences, greater negativity was measured in the left hemisphere for bilateral and LVF compared with RVF targets (p < 0.05), and in the right hemisphere for bilateral compared with LVF targets (p < 0.05).

3.5. N2 component

The ANOVA carried out in the time interval corresponding to the late N2 component (281–300 ms after target onset) showed main effects for Load and Target Position (F(2,38) = 50.30, p < 0.001, GG ε = 0.93, and F(2,38) = 3.73, p < 0.05, GG ε = 0.80, respectively). Relatively greater negativity was found under Visual Dual (0.05 μV) than Single task (1.26 μV, p < 0.05), which, in turn, had significantly greater relative negativity than Auditory Dual task (4.97 μV, all ps < 0.001). Moreover, LVF and RVF stimuli (1.94 and 1.88 μV, respectively) elicited relatively higher negative amplitude compared with bilateral targets (2.45 μV, all ps < 0.05). In addition, the significant Target Position by Hemisphere interaction (F(2,38) = 5.87, p < 0.01, GG ε = 0.89) revealed increased amplitude for LVF and bilateral targets
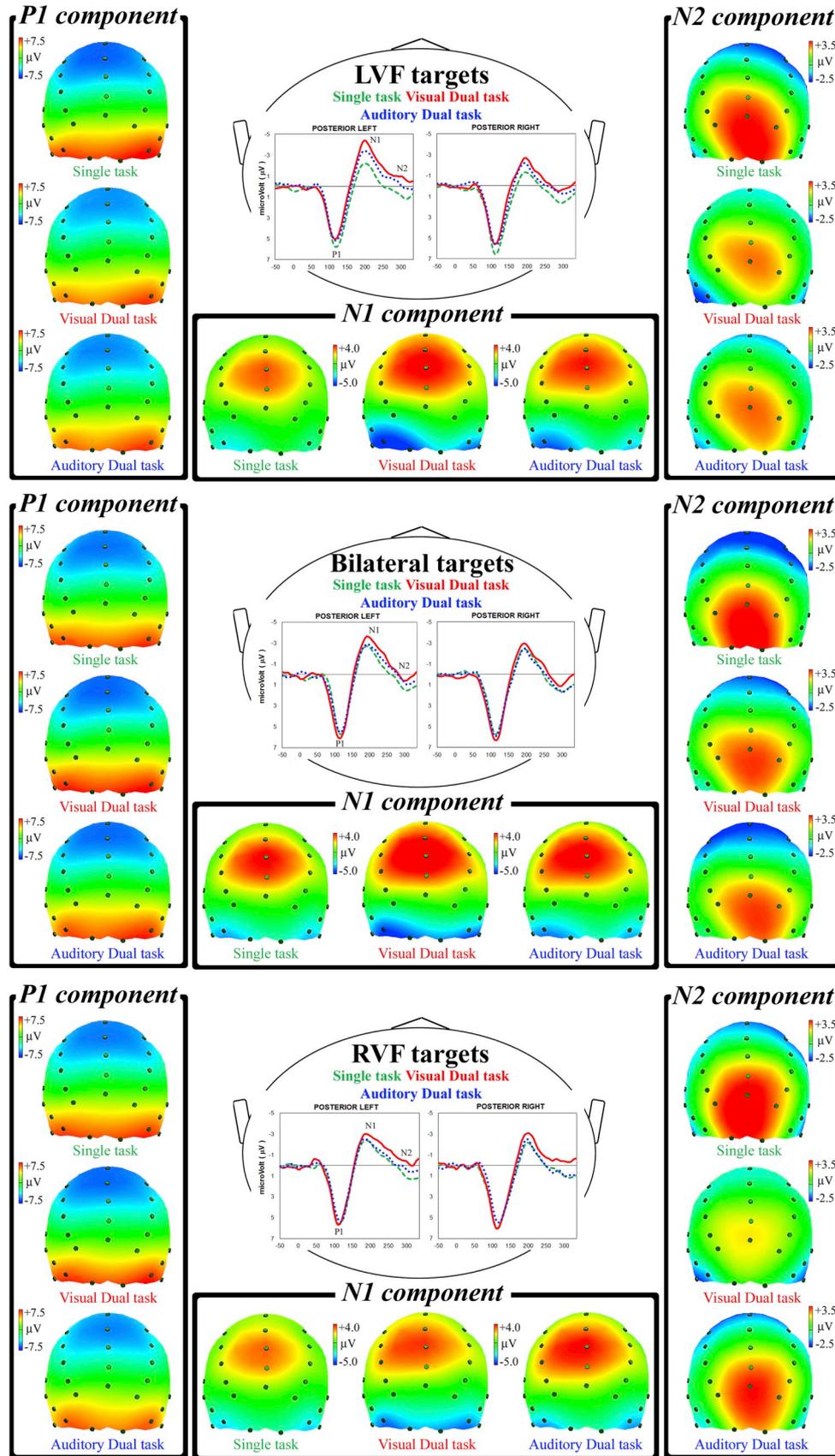
Fig. 2. Grand mean average potential and spline maps of correct targets. P1, N1 and N2 components of the whole group (n = 20), showing LVF (top panel), Bilateral (central panel) and RVF stimuli (bottom panel) during Single (green lines), Visual Dual (red lines) and Auditory Dual task (blue lines). Negativity is shown upwards. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
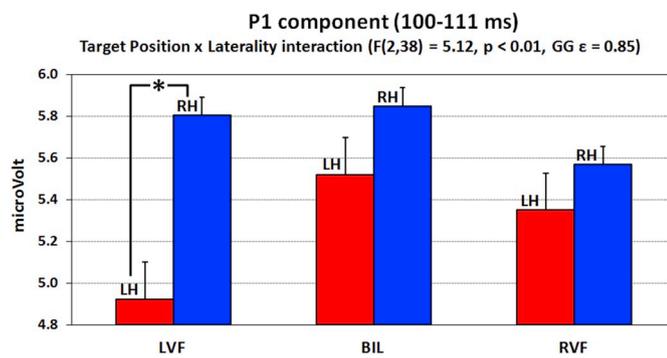
Fig. 3. P1 component elicited on posterior sites. Target Position by Laterality interaction. Bars represent Standard Errors (SE). * significant post-hoc comparisons. LH = Left Hemisphere; RH = Right Hemisphere; LVF = Left Visual Field targets; BIL = Bilateral targets; RVF = Right Visual Field targets.
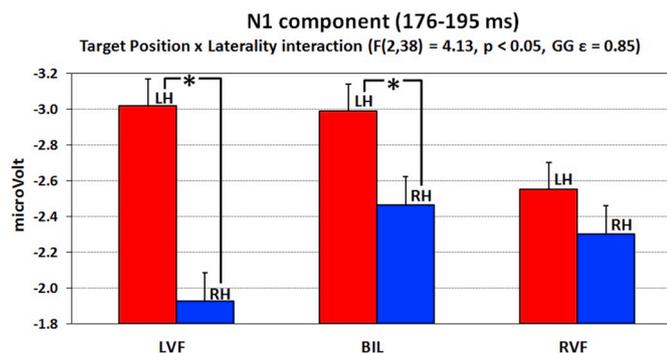

Fig. 4. N1 component elicited on posterior sites. Target Position by Laterality interaction. Bars represent Standard Errors (SE). * significant post-hoc comparisons. LH = Left Hemisphere; RH = Right Hemisphere; LVF = Left Visual Field targets; BIL = Bilateral targets; RVF = Right Visual Field targets.
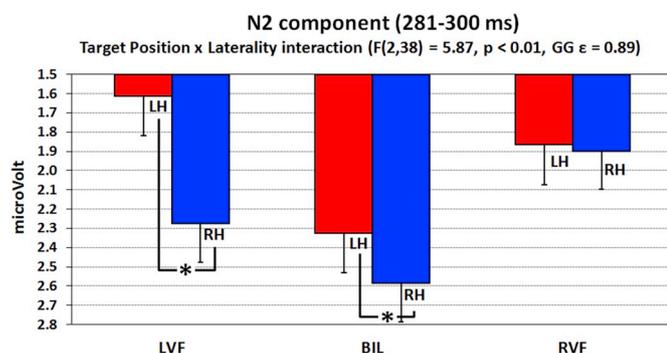

Fig. 5. N2 component elicited on posterior sites. Target Position by Laterality interaction. Bars represent Standard Errors (SE). * significant post-hoc comparisons. LH = Left Hemisphere; RH = Right Hemisphere; LVF = Left Visual Field targets; BIL = Bilateral targets; RVF = Right Visual Field targets.

in the left vs. right hemisphere ($p < 0.001$ and $p < 0.05$, respectively), and a bilateral pattern of activation for RVF targets (Fig. 5).

When considering within-hemispheres differences, greater negativity was found in the left hemisphere for bilateral compared with LVF and RVF targets ($p < 0.001$ and $p < 0.01$, respectively), and in the right hemisphere for LVF and bilateral compared with RVF targets ($p < 0.01$ and $p < 0.001$, respectively).

3.6. Comparison of ERP components for correct vs. error responses to target position

The aim of the analyses reported below was to investigate how the

three previously described ERP components would reflect errors in the spatial monitoring task. We focused on the Visual Dual Task because this condition yielded the largest number of errors (see behavioral results) and included for analysis all participants who had a minimum of 20 artifact-free error trials per condition (which were averaged for ERP analysis; see Fig. 6).

The data from 12 participants who fulfilled the above criteria were submitted to three separate three-way ANOVAs on P1, N1 and N2 time-intervals, with the following factors: Target position (three levels: LVF vs. Bilateral vs. RVF), Response (two levels: Correct vs. Error) and Hemisphere (two levels: Left vs. Right).

3.7. P1 component

The ANOVA carried out in the early time interval corresponding to the P1 component (100–111 ms after target onset) showed a Target Position main effect ($F(2,22) = 5.48$, $p < 0.01$, GG $\varepsilon = 0.98$). Regardless of whether the response was correct or incorrect, bilateral targets (5.44 μV) elicited greater positivity than unilateral (LVF or RVF) targets (4.75 and 4.73 μV, respectively; all ps < 0.05). In addition, a significant Response by Target Position interaction was found (F (2,22) = 3.38, p = 0.05). However, post hoc analysis did not reveal significant differences among conditions.

3.8. N1 component

The ANOVA carried out in the time interval corresponding to the N1 component (176–195 ms after target onset) revealed a significant Response by Target Position by Hemisphere interaction (F (2,22) = 4.76, p < 0.05, GG $\varepsilon = 0.97$). In line with the whole group analysis, for correct responses a significant greater negativity in left than right hemisphere was present for both LVF and bilateral targets (p < 0.001 and p < 0.05, respectively), whereas RVF stimuli elicited a bilateral pattern of activation (Fig. 7, red and blue columns). This pattern characterized also error responses (all ps < 0.001; Fig. 7, red and blue striped columns).

However, considering within-hemisphere differences, significantly greater negativity was found for correct compared with error response to LVF targets in both left (p < 0.01) and right hemisphere (p < 0.05). On the contrary, greater negativity was found for error (compared with correct) responses to bilateral targets in the left hemisphere only (p < 0.01). No differences were found for RVF targets.

3.9. N2 component

The ANOVA carried out in the time interval corresponding to the late N2 component (281–300 ms after target onset) showed a significant Target Position by Hemisphere interaction (F(2,22) = 5.10, p < 0.01, GG $\varepsilon = 0.78$). Again, LVF and bilateral targets elicited greater amplitude in the left vs. right hemisphere (all ps < 0.001), whereas RVF targets yielded a bilateral pattern of activation. With respect to within-hemisphere differences, greater right negativity was measured for RVF compared with both LVF and bilateral targets (p < 0.01). In addition, the ANOVA revealed a significant Response by Target Position interaction (F(2,22) = 3.38, p = 0.05, GG $\varepsilon = 0.72$): both LVF and RVF targets elicited higher negativity in correct compared with error responses (all ps < 0.05; Fig. 8). Finally, we found greater amplitude for RVF than bilateral targets in the correct responses only (p < 0.05). No differences were found between correct and error responses to bilateral targets.

4. Discussion

The present study investigated the neurophysiological correlates associated with correct detection vs. misdetection of peripheral visual

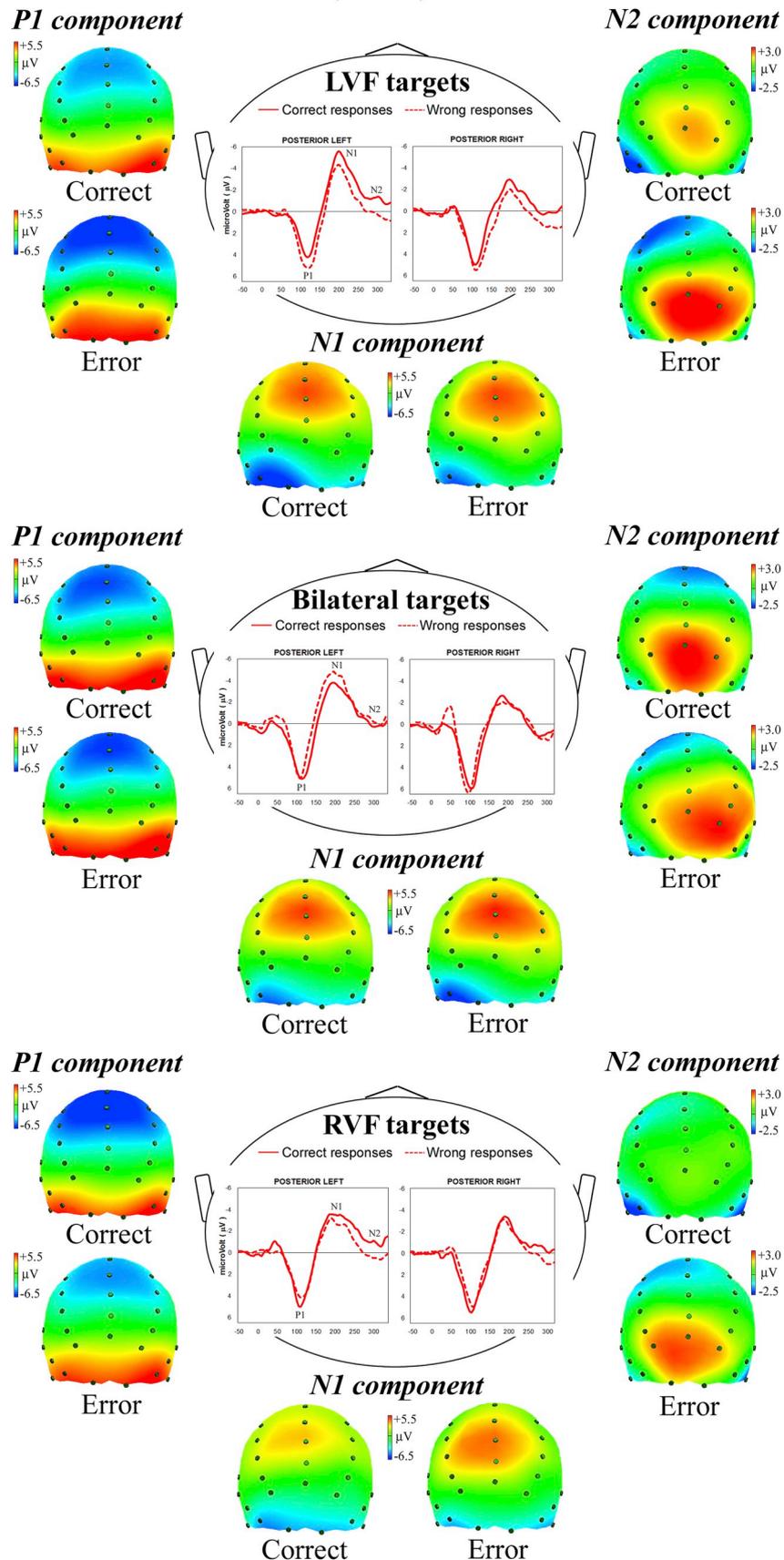# SUB SAMPLE (n=12) - Visual Dual task

Fig. 6. Grand mean average potential and spline maps of correct/error responses. P1, N1 and N2 components of the sub-sample (n = 12), showing correct (full red line) and error (dashed red line) responses elicited by LVF (top panel), Bilateral (central panel) and RVF stimuli (bottom panel) during Visual Dual. Negativity is shown upwards. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
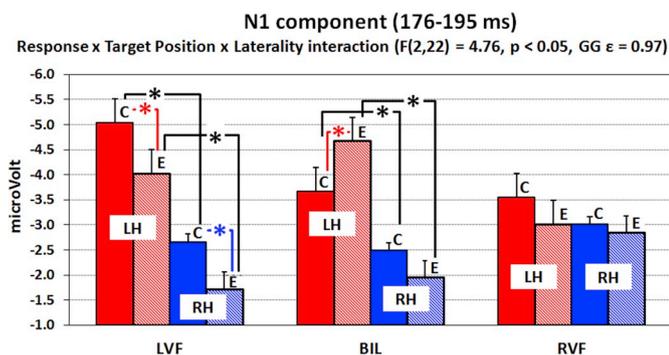
Fig. 7. N1 component elicited on posterior sites in the sub-sample (correct vs. error responses). Response by Target Position by Laterality interaction. Bars represent Standard Errors (SE). * significant post-hoc comparisons. LH = Left Hemisphere; RH = Right Hemisphere; LVF = Left Visual Field targets; BIL = Bilateral targets; RVF = Right Visual Field targets; C = trials corresponding to Correct behavioral responses; E = trials corresponding to Error behavioral responses.
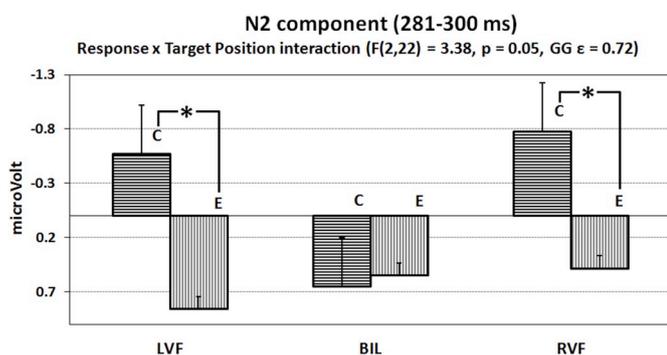

Fig. 8. N2 component elicited on posterior sites in the sub-sample (correct vs. error responses). Response by Target Position interaction. Bars represent Standard Errors (SE). * significant post-hoc comparisons. LVF = Left Visual Field targets; BIL = Bilateral targets; RVF = Right Visual Field targets; C = trials corresponding to Correct behavioral responses; E = trials corresponding to Error behavioral responses.

target(s) under multitasking. The experimental task was based on a paradigm that was previously shown to elicit severe patterns of contralateral omissions in chronic stroke patients (Blini et al., 2016; Bonato et al., 2010, 2013). Importantly, we used visual masking and very short peripheral target duration to increase the difficulty of the primary visuospatial processing task. We therefore expected it to be more susceptible to the effect of multitasking, in analogy with the findings on stroke patients. Our experimental manipulation successfully induced a substantial number of errors, which in turn allowed us to analyze not only the automatic ERP components associated with correct target detection (i.e., P1, N1 and N2 components) but also to contrast the electrophysiological patterns of activation elicited by correct and error trials in a sub-sample of participants.

Participants' behavioral data confirmed the effectiveness of multitasking in increasing task demands, with slower RTs to targets in both Dual tasks in comparison to the Single task condition, and lower accuracy in the Visual Dual compared with both Single and Auditory Dual tasks. The analyses of electrophysiological data carried out on correct trials in the whole group highlighted several correlates of the effect of multitasking on spatial processing. Though there was a hint for a load effect even in the P1 component, the modulation of the ERP was most reliable for the N1 component. As in our previous study (Bonato et al., 2015), the Visual Dual task showed a strong load effect in comparison with both the Single and the Auditory Dual task. It is important to emphasize that not only the lateralized target(s), but also the other two

types of stimuli (i.e., the central shape and the sound) were always presented in all conditions, even when they were task-irrelevant. By manipulating only task instructions and keeping constant the sensory information available to the participants, we therefore obtained a pure measure of the top-down attentional load induced by multitasking. The cross-modal load condition (i.e., Auditory Dual task) included in our paradigm is then useful to disentangle a modality-specific (i.e., visual) effect of multitasking from a more general effect of dividing attention across different sensory channels. In this respect, the higher N1 amplitude observed in the Visual Dual task compared to the Auditory Dual task suggests that intra-modal load is more challenging, therefore we cannot exclude that the difference in amplitude reflects task difficulty (i.e., intra-modal load induced more errors than cross-modal load). With respect to our previous study, in which the load effect was reliable in the P1 component interval, in the present study a load main effect emerged in the N1 component temporal window (not significant in our past work). This shift from P1 to N1 component might be the consequence of the small, but critical, changes adopted in the experimental paradigm, which resulted in a drastically more difficult target detection, as documented by a much larger number of errors. In particular, accuracy in the Visual Dual task (i.e., the most difficult condition due to the intra-modal competition for attention resources) dropped from 98% in the previous study (Bonato et al., 2015) to 57% in the current one. Therefore, the modulation of the N1 amplitude would be the consequence of the recruitment of additional cognitive resources necessary for processing concurrent stimuli (Hillyard et al., 1998). However, the N1 modulation might also be related to the different task requirements across conditions. That is, the dual task condition required a discrimination task (shape or tone classification) in addition to the target detection task that was constant across conditions. The additional discrimination task might have enhanced the N1 potential, in line with previous evidence showing that this component reflects discrimination processes (Vogel and Luck, 2000). Notwithstanding the P1/N1 difference, it is important to note that load had stronger impact on the Visual Dual task, i.e., the condition in which all task-relevant information required intra-modal processing, compared to the cross-modal condition (Auditory Dual task). This finding is difficult to reconcile with the hypothesis that the enhanced N1 simply reflects the additional discrimination process implied by the dual task conditions.

A second, important result was the reliable, different pattern of activation that characterized left vs. right visual field targets (i.e., a posterior lateralization for LVF and a bilateral activation for RVF stimuli). This finding clearly mirrors a genuine neural response to stimuli appearing across different positions and suggests that the mask had no effect on automatic ERP analysis of lateralized targets, in agreement with the results of our previous study with a different sample of participants (Bonato et al., 2015). This pattern of activation was not only present in all the ERP components analyzed for the whole group, but also in the sub-sample selected for the analysis of correct vs. error responses.

Compared with our previous research in which bilateral targets were administered but not analyzed (for technical details, see Bonato et al., 2015), the introduction of a bilateral key-press response in the present study allowed us to include also bilateral targets in our statistical analyses. Thus, the third important finding was the electrophysiological pattern of activation elicited by bilateral stimuli: significantly lateralized, broadly resembling the activation triggered by LVF targets. This result might allow us to better understand the biased competitive attentional mechanisms present in brain-damaged patients suffering from unilateral spatial neglect. After several months from stroke some patients no longer omit single contralesional targets, but they start missing them only when an ipsilesional, competing target is concurrently presented (extinction), which is sometimes conceptualized as mild neglect (Kaplan et al., 1995). Since bilateral stimuli elicited, in the present study, a pattern of activation similar to that highlighted by LVF targets in the ERP components analyzed (i.e., N1 and N2), it is not

surprising that right hemisphere damage affects not only the LVF, but also bilateral stimulus processing. Future studies on right-hemisphere damaged patients with different severity of unilateral spatial neglect/extinction will allow us to determine what really happens in the cortical pathway of lateralized and bilateral stimulus processing.

The present research was also aimed at assessing how and when visual information processing under multitasking leads to different behavioral (i.e., correct vs. error) responses. To the best of our knowledge, electrophysiological literature on multitasking providing evidence on the way correct and error responses are processed is still lacking. We therefore hypothesized two possible outcomes. On the one hand, the pattern of activation might be similar for correct and error responses, the latter showing reduced ERP amplitude with respect to the former, thereby suggesting a threshold criterion underlying behavioral accuracy. On the other hand, the same stimuli might elicit diverging patterns of activation at a given time-point, thereby producing clear-cut differences between ERPs related to correct vs. incorrect responses. We observed for LVF and bilateral targets a clear electrophysiological signature of the error responses at the level of the N1 component, i.e., when stimulus information reaches visuo-associative areas. Both these stimulus positions, associated with correct and error responses, elicited the same left-lateralized pattern of activation: however, correct responses to LVF targets were associated with significantly greater N1 amplitude in both left and right posterior regions of interest than LVF target errors. In contrast, correct responses to bilateral targets showed significantly smaller N1 amplitude in left hemisphere than error responses to the same stimuli. With respect to RVF targets, which always elicited bilateral activation, the difference between correct and error responses was evident in the late ERP component, i.e., the N2. This "delay" in RVF stimulus processing was also found in our previous study during the Visual Dual task (Bonato et al., 2015). This pattern of results suggests that the mechanism underlying the processing of visual information – within a multitasking context – is based on a threshold criterion: when the critical N1 component amplitude is reached, subsequent processing along the whole pathway leads to awareness and, in turn, to a correct behavioral response. In contrast, behavioral errors are associated with below-threshold N1 (LVF targets) or N2 amplitude (RVF targets) for unilateral targets, as well as over-threshold N1 values for bilateral targets. In other words, the electrophysiological signature of stimulus position is already altered about 176–195 ms after target onset, well before the behavioral response (which is completed at least 500 ms later - around 700 ms for the Visual Dual task), thus supporting the hypothesis that the physiological mechanism underlying correct performance is grounded on a threshold criterion. The electrophysiological pattern of N1 activation underlying correct responses and errors provides some insights, albeit speculative, when related to the heterogeneous findings on early ERP components during visual processing in right hemisphere stroke patients. In Marzi et al. (2000), a right-hemisphere damage patient showed typical P1 and N1 amplitudes to LVF visual stimuli; however, no sign of evoked potentials was found for extinguished stimuli. In another stroke patient studied by Vuilleumier et al. (2001), the P1 component exhibited the same pattern of activation/lack of activation for perceived/extinguished visual stimuli as Marzi et al. (2000)'s patient, whereas the N1 amplitude was similar for both extinguished and detected stimuli. In reviewing these limited and mixed results on very few patients, Deouell (2002) suggested that extinguished visual stimuli result in neural responses at extrastriate sites, but at least some of these early responses may be diminished. In line with the results of the present study, he also hypothesized a threshold mechanism, whereby only stimuli that drive amplitude or duration of evoked potentials beyond some threshold may become conscious.

The idea of a threshold criterion underlying correct stimulus detection under multitasking can be framed within information processing theories that emphasize capacity-limited resources (e.g., Duncan, 1980; Marois and Ivanoff, 2005; Tombu et al., 2011). In particular,

capacity limits represent a classic explanation of phenomena such as the attentional blink (Marois and Ivanoff, 2005). Also the results from the present study support the capacity-limited resource model, especially considering the significant decreased behavioral performance on Visual Dual task after the experimental manipulations used in the current version of our load task.

In summary, we carried out an ERP investigation of how spatial monitoring (visual detection of lateralized targets) is affected by concurrent task demands that require additional processing of visual or auditory stimuli. Our multitasking paradigm induced a consistent number of target detection errors in healthy participants, therefore allowing for a more direct comparison with the impaired performance of brain-damaged patients. ERP components revealed both the effect of multitasking and, for the first time in the present paradigm, the pattern of posterior left activation for bilateral targets when stimulus information spread to visuo-associative areas (N1 component), a condition that did not reach the threshold criterion adopted for unilateral (i.e., LVF) stimuli, and that might be seen as representative of those contexts where right-hemisphere damage patients report the right stimulus only. Finally, the complementary error analyses carried out on a sub-sample of participants suggests that the mechanism underlying the processing of visual information – within a multitasking context – is based on a threshold criterion, that in turn leads to a correct response or a behavioral error.

CRediT authorship contribution statement

Zaira Romeo: Conceptualization, Data curation, Investigation, Formal analysis, Writing - original draft, Writing - review & editing. **Mario Bonato:** Conceptualization, Investigation, Methodology, Supervision, Writing - review & editing. **Marco Zorzi:** Conceptualization, Funding acquisition, Investigation, Supervision, Writing - review & editing. **Chiara Spironelli:** Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Writing - review & editing.

References

Al-Hashimi, O., Zanto, T.P., Gazzaley, A., 2015. Neural sources of performance decline during continuous multitasking. Cortex 71, 49–57. https://doi.org/10.1016/j.cortex.2015.06.001.

Blini, E., Romeo, Z., Spironelli, C., Pitteri, M., Meneghello, F., Bonato, M., Zorzi, M., 2016. Multi-tasking uncovers right spatial neglect and extinction in chronic left-hemisphere stroke patients. Neuropsychologia 92, 147–157. https://doi.org/10.1016/j.neuropsychologia.2016.02.028.

Bonato, M., 2012. Neglect and extinction depend greatly on task demands: a review. Front. Hum. Neurosci. 6 (July), 1–13. https://doi.org/10.3389/fnhum.2012.00195.

Bonato, M., Priftis, K., Marenzi, R., Umiltà, C., Zorzi, M., 2010. Increased attentional demands impair contralesional space awareness following stroke. Neuropsychologia 48 (13), 3934–3940. https://doi.org/10.1016/j.neuropsychologia.2010.08.022.

Bonato, M., Priftis, K., Marenzi, R., Umiltà, C., Zorzi, M., 2012. Deficits of contralesional awareness: a case study on what paper-and-pencil tests neglect. Neuropsychology 26 (1), 20–36. https://doi.org/10.1037/a0025306.

Bonato, M., Priftis, K., Umiltà, C., Zorzi, M., 2013. Computer-based attention-demanding

testing unveils severe neglect in apparently intact patients. Behav. Neurol. 26 (3), 179–181. https://doi.org/10.3233/BEN-2012-129005.

Bonato, M., Spironelli, C., Lisi, M., Priftis, K., Zorzi, M., 2015. Effects of multimodal load on spatial monitoring as revealed by ERPs. PLoS One 10 (9), 1–21. https://doi.org/10.1371/journal.pone.0136719.

Chen, Y., Spence, C., 2017. Hemispheric asymmetry: looking for a novel signature of the modulation of spatial attention in multisensory processing. Psychon. Bull. Rev. 24, 690–707. https://doi.org/10.3758/s13423-016-1154-y.

Deouell, L.Y., 2002. Pre-requisites for conscious awareness: clues from electro-physiological and behavioral studies of unilateral neglect patients. Conscious. Cognit. 11 (4), 546–567. https://doi.org/10.1016/S1053-8100(02)00024-7.

Ding, Y., Martinez, A., Qu, Z., Hillyard, S.A., 2014. Earliest stages of visual cortical processing are not modified by attentional load. Hum. Brain Mapp. 35 (7), 3008–3024. https://doi.org/10.1002/hbm.22381.

Duncan, J., 1980. The demonstration of capacity limitation. Cogn. Psychol. 12 (1), 75–96. https://doi.org/10.1016/0010-0285(80)90004-3.

Fu, S., Zinni, M., Squire, P.N., Kumar, R., Caggiano, D.M., Parasuraman, R., 2008. When and where perceptual load interacts with voluntary visuospatial attention: an event-related potential and dipole modeling study. Neuroimage 39 (3), 1345–1355. https://doi.org/10.1016/j.neuroimage.2007.09.068.

Handy, T.C., Soltani, M., Mangun, G.R., 2001. Perceptual load and visuocortical processing: event-related potentials reveal sensory-level selection. Psychol. Sci. 12 (3), 213–218. https://doi.org/10.1111/1467-9280.00338.

Hillyard, S.A., Vogel, E.K., Luck, S.J., 1998. Sensory gain control (amplification) as a mechanism of selective attention: electrophysiological and neuroimaging evidence. Philos. Trans. R. Soc. Biol. Sci. 353 (1373), 1257–1270. https://doi.org/10.1098/rstb.1998.0281.

Holländer, A., Corballis, M.C., Hamm, J.P., 2005. Visual-field asymmetry in dual-stream RSVP. Neuropsychologia 43 (1), 35–40. https://doi.org/10.1016/j.neuropsychologia.2004.06.006.

Kaplan, R.F., Cohen, R.A., Rosengart, A., Elsner, A.E., Hedges, T.R., Caplan, L.R., 1995. Extinction during time controlled direct retinal stimulation after recovery from right hemispheric stroke. J. Neurol. Neurosurg. Psychiatry 59, 534–536. https://doi.org/10.1136/jnnp.59.5.534.

Koch, I., Poljac, E., Müller, H., Kiesel, A., 2018. Cognitive structure, flexibility, and plasticity in human multitasking-an integrative review of dual-task and task-switching research. Psychol. Bull. 144 (6), 557–583. https://doi.org/10.1037/bul0000144.

Lavie, N., 1995. Perceptual load as a necessary condition for selective attention. J. Exp. Psychol. Hum. Percept. Perform. 21 (3), 451–468. https://doi.org/10.1037/0096-1523.21.3.451.

Lavie, N., 2005. Distracted and confused?: selective attention under load. Trends Cogn. Sci. 9 (2), 75–82. https://doi.org/10.1016/j.tics.2004.12.004.

Lisi, M., Bonato, M., Zorzi, M., 2015. Pupil dilation reveals top-down attentional load during spatial monitoring. Biol. Psychol. 112, 39–45. https://doi.org/10.1016/j.biopsycho.2015.10.002.

Marois, R., Ivanoff, J., 2005. Capacity limits of information processing in the brain. Trends Cogn. Sci. 9 (6), 296–305. https://doi.org/10.1016/j.tics.2005.04.010.

Marzi, C.A., Girelli, M., Miniussi, C., Smania, N., Maravita, A., 2000. Electrophysiological correlates of conscious vision: evidence from unilateral extinction. J. Cogn. Neurosci. 12 (5), 869–877. https://doi.org/10.1162/089892900562471.

Nijboer, M., Borst, J.P., van Rijn, H., Taatgen, N.A., 2016. Driving and multitasking: the good, the bad, and the dangerous. Front. Psychol. 7 (NOV), 1–16. https://doi.org/10.3389/fpsyg.2016.01718.

O'Connell, R.G., Schneider, D., Hester, R., Mattingley, J.B., Bellgrove, M.A., 2011. Attentional load asymmetrically affects early electrophysiological indices of visual orienting. Cerebr. Cortex 21 (5), 1056–1065. https://doi.org/10.1093/cercor/bhq178.

Oldfield, R.C.C., 1971. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia 9 (1), 97–113. https://doi.org/10.1016/0028-3932(71)90067-4.

Oostenveld, R., Praamstra, P., 2001. The five percent electrode system for high-resolution EEG and ERP measurements. Clin. Neurophysiol. 112 (4), 713–719. https://doi.org/10.1016/S1388-2457(00)00527-7.

Rorden, C., Guerrini, C., Swainson, R., Lazzeri, M., Baylis, G.C., 2008. Event related potentials reveal that increasing perceptual load leads to increased responses for target stimuli and decreased responses for irrelevant stimuli. Front. Human Neurosci. 2, 1–7. https://doi.org/10.3389/neuro.09.004.2008.

Sasai, S., Boly, M., Mensen, A., Tononi, G., 2016. Functional split brain in a driving/listening paradigm. Proc. Natl. Acad. Sci. 113 (50), 14444–14449. https://doi.org/10.1073/pnas.1613200113.

Schaefer, S., 2014. The ecological approach to cognitive-motor dual-tasking: findings on the effects of expertise and age. Front. Psychol. 5. https://doi.org/10.3389/fpsyg.2014.01167.

Tombu, M.N., Asplund, C.L., Dux, P.E., Godwin, D., Martin, J.W., Marois, R., 2011. A Unified attentional bottleneck in the human brain. Proc. Natl. Acad. Sci. 108 (33), 13426–13431. https://doi.org/10.1073/pnas.1103583108.

Verleger, R., Möller, F., Kuniecki, M., Śmigasiewicz, K., Groppa, S., Siebner, H.R., 2010. The left visual-field advantage in rapid visual presentationis amplified rather than reduced by posterior-parietal rTMS. Exp. Brain Res. 203 (2), 355–365. https://doi.org/10.1007/s00221-010-2237-z.

Verleger, R., Śmigasiewicz, K., 2015. Consciousness wanted, attention found: reasons for the advantage of the left visual field in identifying T2 among rapidly presented series. Conscious. Cognit. 35, 260–273. https://doi.org/10.1016/j.concog.2015.02.013.

Vogel, E.K., Luck, S.J., 2000. The visual N1 component as an index of a discrimination process. Psychophysiology 37 (2), 190–203. https://doi.org/10.1017/S0048577200981265.

Vuilleumier, P., Sagiv, N., Hazeltine, E., Poldrack, R.A., Swick, D., Rafal, R.D., Gabrieli, J.D.E., 2001. Neural fate of seen and unseen faces in visuospatial neglect: a combined event-related functional MRI and event-related potential study. Proc. Natl. Acad. Sci. 98 (6), 3495–3500. https://doi.org/10.1073/pnas.051436898.