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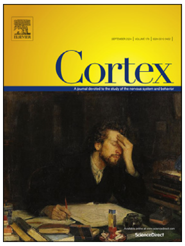

Research Report

The engagement of temporal attention in left spatial neglect

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ABSTRACT

Previous literature showed how left spatial neglect arises from an asymmetrical distribution of spatial attention. However, it was also suggested that left spatial neglect might be partially caused or at least worsened by non-spatial attention disorders of the right-lateralized stimulus-driven attentional fronto-parietal network. Here, we psychophysically tested the efficiency of temporal attentional engagement of foveal perception through meta-contrast (Experiment 1) and "attentional" masking (Experiment 2) tasks in patients with right-hemisphere stroke with left neglect (N+), without left neglect (N-) and matched healthy controls (C). In both experiments, N+ patients showed higher thresholds, not only than Cs, but also than N- patients. Temporal engagement was clinically impaired in all N+ patients and highly correlated with their typical inability to direct spatial attention towards stimuli on the left side. Our findings suggest that a temporal impairment of attentional engagement is a relevant deficit of left spatial neglect.

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1. Introduction

Patients affected by left spatial neglect are unable to detect events on the left side of space, despite apparently normal sensory processing, and are affected by a spatial bias for directing actions towards the left side of the bodily or extra-bodily space (Driver & Mattingley, 1998; Karnath & Rorden, 2012). Left spatial neglect has attracted tremendous interest as a model for understanding both the neurobiological basis of visual awareness and cerebral lateralization as well as spatial cognition. However, its neurocognitive bases remain poorly understood (Moore et al., 2023).

Although decades of neuropsychological testing in split-brain patients and clinical studies in patients with unilateral brain lesions (e.g., superior parietal lobe, SPL; Mesulam, 1981; Sperry, 1974) have led to the assumption that visual spatial attention is primarily a function of the right hemisphere, further studies showed that spatial attention is a largely bilateral system. Accordingly, right spatial neglect can be also observed in patients with left hemisphere damage (Beis et al., 2004; Ten Brink et al., 2017).

A second temporal attentional system is mainly lateralized to the right hemisphere. This attentional network detects behaviorally relevant stimuli, and works as an alerting or re-orienting circuit for the bilateral spatial attention network when salient or unexpected events are detected outside the current focus of spatial attention (for reviews, see Corbetta & Shulman, 2002, 2011; Van Vleet et al., 2020).

Corbetta and Shulman (2002; 2011) proposed an intriguing anatomical and physiological model in which this right attentional network could have a crucial role in explaining the complexity of left spatial neglect syndrome (see also Battelli et al., 2001, 2003; for a review, see Battelli et al., 2007). In humans, lesions to the right inferior parietal lobe (IPL) could lead to left spatial neglect. This finding supports that the right IPL plays an important role also for the spatial attention re-orienting system (Friedrich et al., 1998; Posner et al., 1984; Corbetta et al., 2008; Rengachary et al., 2011; see Losier & Klein, 2001 for a meta-analysis). However, consistent brain imaging and lesion studies have revealed that the IPL also has temporal functions, such as sustaining and alerting attention (Robertson et al., 1998; Rueckert & Grafman, 1996; Van Vleet et al., 2020; Wilkins et al., 1987; Husain et al., 1997; Husain & Nachev, 2007 for reviews, see Corbetta & Shulman, 2011; Husain & Rorden, 2003).

A right lesion within the border of the IPL and the temporal lobe, is considered a possible neuroanatomical substrate of neglect (Corbetta & Shulman, 2011; Husain & Rorden, 2003; Karnath, 2015). However, neglect has also been associated with a wide range of damaged brain areas, including the temporo-parietal cortex, the frontal cortex, the occipital cortex, and the cerebellum. Neglect has also been reported in patients with lesions to subcortical areas and following disconnection of the superior longitudinal, inferior longitudinal, and inferior fronto-occipital fasciculi (for a recent systematic review, see Moore et al., 2023). Accordingly, neglect could be better understood if considered as a disconnection syndrome rather than a deficit linked back to a single damaged brain area (Saxena et al., 2022; Bartolomeo et al., 2007).

The right temporoparietal junction (TPJ) has been identified as part of a larger attentional network including the right superior temporal gyrus (STG) (Battelli et al., 2007). When we identify an object (i.e., attentional engagement), our ability to detect a second object (i.e., attentional disengagement) is impaired if it appears within 400 msec after the first one (Husain et al., 1997; Shapiro et al., 2002). This phenomenon has been termed attentional blink or dwell time, and it is a measure of our ability to desengagement temporal attention from a previous object to a new one. Neglect patients with right parietal, frontal or basal nuclei lesions present an abnormally severe and protracted attentional blink (Husain et al., 1997). Importantly, lesions to the right TPJ lead to a prolonged attentional blink compared to lesions of the right SPL (Shapiro et al., 2002). These findings suggest that the right diffuse attentional network makes an important contribution also to temporal disengagement of attention (Husain & Nachev, 2007), as precisely predicted by the "re-orienting" (Corbetta & Shulman, 2011) and the "when" system (Battelli et al., 2007). Thus, evidence has suggested that the spatial attention deficits of the bilateral SPL could arise from an impaired right diffuse attentional network supporting arousal/vigilance, re-orienting/disengagement (Corbetta & Shulman, 2011) or temporal resolution of attention (Battelli et al., 2007; Husain & Nachev, 2007). A systematic review has shown that, by manipulating the stimulus exposure time, the temporal attention was prolonged in patients with right lesions, irrespective of whether patients presented spatial neglect (Low et al., 2017).

In our study, we investigate foveal perception, measuring the engagement of temporal attention in two psychophysical experiments comparing two matched groups of right hemisphere-damaged patients—one with (N+) and one without (N-) left spatial neglect—and a matched healthy control group (C).

In the first experiment, we used a meta-contrast masking task to measure the temporal attention engagement of a visual event. The mask contours were closely fitted but did not overlap with the target contours. This manipulation allowed us to understand whether the foveal temporal attention is impaired in left spatial neglect patients. In particular, we predicted that: the mean threshold (i.e., measured as stimulus-onset-asynchrony, SOA between target and mask in msec) for the accuracy in target identification in N+ patients should be higher in comparison to C and N- patients.

In the second experiment, we investigated the effect of an irrelevant visual event (i.e., the second stimulus), employing, as masks, the same letters and the same location used for the targets. However, on each trial, the target and mask letters were different. By using this procedure, we were able to quantify the "attentional-substitution" rate of the target (the first letter) with the mask (the second letter). For attentional-substitution we hypothesize that neglect patients should more frequently report the second irrelevant letter (i.e., the mask) rather than the first relevant one (i.e., the target). In particular, if the engagement of temporal attention is really damaged in left spatial neglect, we predicted that: i) the mean threshold for the accuracy in target identification in N+ patients should be higher in comparison to C and N- patients, and ii) that at the shortest target-mask SOA only N+ patients should more frequently present attentional-substitution.

We predicted that the general rule of temporal priority entry - according to which the first stimulus is always better perceived in comparison to the following events - could be not respected specifically in patients with left spatial neglect, demonstrating their extremely labile initial stage of attentional engagement. Potter et al. (2002) experimentally simulated this labile first attentional stage by using short stimuli durations, showing that it is possible to nullify the typical temporal priority entry of the events also in healthy individuals. Thus, whether in left neglect patients the first attentional stage is delayed, it could largely interfere also with their consecutive perceptual awareness and their working memory abilities. Previous studies found, indeed, spatial working memory deficits in patients with left spatial neglect (Ferber & Danckert, 2006; Malhotra et al., 2005, 2004; Pisella et al., 2004; Ravizza et al., 2005; Wansard et al., 2015, 2014; Fabius et al., 2020). One possibility is that the spatial working memory deficit could be a consequence of the delayed attentional mechanism found in our data (Awh & Jonides, 2001; Cowan & Morey, 2006; Gazzaley & Nobre, 2012; Myers et al., 2017).

Our study could provide the first evidence regarding a temporal attention engagement disorder in the central visual field, in patients with left spatial neglect syndrome.

2. Methods

2.1. *Participants*

Participants provided written informed consent according to the declaration of Helsinki, and procedures were approved by the research ethics committees of the “Villa Beretta” Rehabilitation Hospital in Costamasnaga (LC), Italy. No part of the study procedures was pre-registered prior to the research being conducted. No part of the study analyses was pre-registered prior to the research being conducted. All data exclusions in the samples and all the inclusion/exclusion criteria, were established prior to data analysis, all manipulations, and all measures in the study. Three different groups participated in the present study: Two groups of patients with a right-hemisphere stroke and a group of healthy participants. All groups were matched for years of age and education. Nineteen patients with a first-ever focal right-hemisphere stroke, involving the territory of the middle cerebral artery, participated in the study. Patients had a mean time since stroke of 197 days (SD = 247). No patient was tested within two weeks of their stroke (minimum 41 days) to avoid effects of the acute phase of stroke recovery (Stone et al., 1993), which sometimes differ both in terms of lesion anatomy (Karnath et al., 2001) and in deficit severity.

All patients were right-handed. The neuropsychological assessment for spatial neglect involved a standard procedure including the Bells Cancellation (Gauthier et al., 1989) and the Line Bisection test (Ferber & Karnath, 2001). In order to rule out constructive apraxia frequently associated with spatial neglect syndrome, we excluded from the typical neuropsychological assessment the Copying Drawings test and the Clock test (Halligan et al., 1991). On the basis of clinical observation and formal testing using Bell Cancellation and Line Bisection tests, nine patients showed signs of left neglect (N+ group, four males, mean age: 51 years, standard deviation, SD = 12), whereas 10 control patients with a right-hemisphere stroke did not present any signs of left neglect (N- Group; six males, mean age 54 years-old, SD = 10). The two groups were matched for chronological age, years of education, and days since their stroke (all ps > .18). All patients were recruited from the “Villa Beretta” Rehabilitation Hospital in Costamasnaga (LC), Italy.

Data were also available for a group of nine adults without any declared neurological disease history (C Group, four males), who were recruited from retirement villages and newsletter advertisements for quantitative comparison to the right-hemisphere patients. The mean age of the participants was 45 years (SD = 17). Visual acuity was checked for all participants of the three groups using the standardized procedure for the Snellen Chart test and eye glasses were worn when required. No participant was excluded from the study based on the results in the visual acuity test. The group of healthy adults did not significantly differ from the two right-hemisphere patient groups for age (years) and education years (independent-samples *t*-tests, all ps > .16; see Table 1). The conditions of our ethics approval do not permit public archiving of anonymized study data. Readers seeking access to the data should contact the lead author Simone Gori. Access will be granted to named individuals in accordance with ethical procedures governing the reuse of sensitive data. Specifically, requestors must meet the following conditions to obtain the data: completion of a statement specifying the scientific nature of the data request.

2.2. *Stimuli and procedures: experiment 1 (meta-contrast masking task)*

In this experiment, we used a meta-contrast masking task to measure the temporal attention engagement of a visual event. The mask contours were closely fitted but did not overlap with the target contours. In particular, the mask was composed of four digital eight-like figures displayed near the letter location (see Fig. 1).

Participants performed a single target identification task in which they monitored a centrally attended letter followed by a visual mask (backward masking procedure). The experiments were conducted in a dimly lit and a quiet room. Stimuli were presented on a laptop computer with a liquid crystal display, positioned at approximately 40 cm in front of the seated participant. Each trial began with the onset of a centrally presented fixation mark consisting of a cross (.3 deg of visual angle). After 500 msec a letter obtained by removing line segments from digital 8-like figures (1 × .5 deg) was presented for 40 msec in the center of the screen. The visual mask was displayed for 500 msec after six randomized possible target-mask stimulus onset asynchronies (SOAs; i.e., 40, 80, 120, 200, 520, or 1000 msec). After a 400 msec blank screen, participants had to identify the target choosing between the four possible letters displayed on the screen until their response was provided (chance level = 25%).

Table 1 – Group (C = matched healthy controls, N- = control patients with a right-hemisphere stroke without any signs of left spatial neglect, and N+ = patients with left spatial neglect), chronological age (years-old), years of education (years), days since stroke (days), lesion description (from original clinical report), and severity of the left spatial neglect indexed by "Bells cancellation" test (i.e., omissions on the left side ≥ 6 = presence of left spatial neglect) are reported.

Group	Age	Years of education	Days since stroke	Lesion description	Severity of the left spatial neglect*
C	58	8			
C	65	5			
C	34	18			
C	31	18			
C	72	5			
C	34	18			
C	22	16			
C	45	16			
C	45	18			
N-	43	13	115	Right-hemisphere stroke, involving the territory of the middle cerebral artery with internal carotid artery dissection	4
N-	51	13	376	Right-hemisphere cerebral hemorrhage, involving the territory of the middle cerebral artery with 7 days of non-responsiveness, plus brain surgery	1
N-	58	13	126	Right-hemisphere stroke, involving the territory of the middle cerebral artery plus right thalamic area	0
N-	35	13	720	Right-hemisphere stroke, involving the territory of the middle cerebral artery with softening of the right perisylvian white matter with internal carotid artery dissection	0
N-	49	13	136	Right-hemisphere stroke, involving the territory of the middle cerebral artery	0
N-	54	8	48	Right-hemisphere stroke, involving the territory of the middle cerebral artery	0
N-	66	13	90	Right frontal intraparenchymal hemorrhage with ventricular flooding involving the territory of the middle cerebral artery associated with a period of non-responsiveness	1
N-	65	8	984	Ischemic stroke, involving the territory of the middle cerebral artery, right insular ischemic softening white matter plus involvement of the basal nuclei	4
N-	56	8	58	Small probable multi-infarction outcomes at the ponto-mesencephalic level bilaterally. Right middle cerebral artery area. Further lacunar lesion in the right thalamic area	4
N-	65	8	48	Right-hemisphere stroke, involving the territory of the middle cerebral artery and the right basal nuclei	0
N+	62	5	57	Right-hemisphere stroke with middle cerebral artery hyperdensity	**16**
N+	31	11	61	Subarachnoid hemorrhage due to right middle cerebral artery rupture with associated period of non-responsiveness	**12**
N+	53	13	41	Right-hemisphere stroke, involving the territory of the middle cerebral artery in a known setting of thrombotic thrombocytopenic purpura	**17**
N+	43	13	151	Subarachnoid hemorrhage due to right middle cerebral artery rupture with associated period of non-responsiveness	**17**
N+	61	8	184	Internal right carotid occlusion; large ischemic area in the territory of the middle cerebral artery	**17**
N+	61	5	191	Outcomes of right -hemisphere stroke. Extensive area of poromalacic hypodensity in correspondence with the territory of the middle cerebral artery, right temporal region and basal nuclei	**17**
N+	46	11	121	Subarachnoid hemorrhage due to rupture of the basilar artery apex aneurysm, involvement of the territory of the middle cerebral artery	**17**
N+	36	13	137	Extensive right parietal intraparenchymal hemorrhage of 7 cm. determining mass effect and midline drift. Right middle cerebral artery ectasia at the trifurcation.	16
N+	64	13	107	Subarachnoid hemorrhage involving the territory of the middle cerebral artery because of traumatic brain injury, with associated period of non-responsiveness (3 weeks)	8

Each participant was instructed to use all the time he/she needed to identify the target as accurately as possible. The target accuracy rate was measured. To exclude any motor response by the participants, the experimenter entered the responses, by pressing the corresponding key on the computer keyboard. No feedback was provided to the participants. The session consisted of 72 trials (12 trials for 6 target-mask SOAs). Participants viewed the sequence of stimuli binocularly and were trained to keep their eyes on the fixation mark throughout the duration of the trial. We used a video-camera system to check the fixation. All visual stimuli were black (luminance = .6 cd/m2), whereas the background was white (luminance = 119 cd/m2).

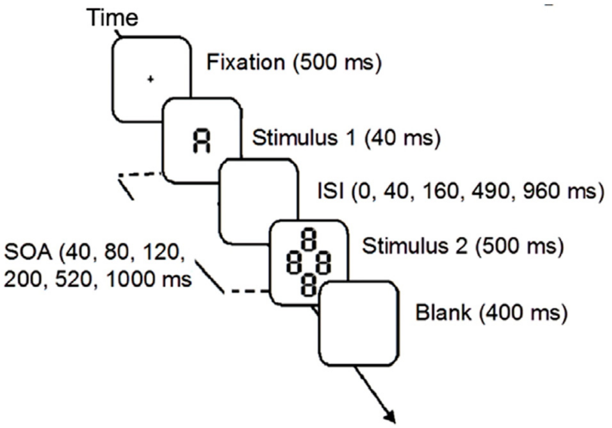

Fig. 1 – Sequence of the visual events during the meta-contrast masking task (Experiment 1).

2.3. *Stimuli and procedures: experiment 2 ("Attentional" masking task)*

To investigate the effect and fate of an irrelevant visual event (i.e., the second stimulus), we employed the same letters used for the targets as masks (i.e., pattern mask). However, on each trial, the target and mask letters were always different. By using this procedure, we were able to quantify the "attentional-substitution" rate of the target (the first letter) with the mask (the second letter).

Stimuli and procedures were the same as the Experiment 1 (Meta-contrast masking task). The only difference was the type of the employed mask. A typical pattern mask (in which contours of the mask are spatially superimposed on the contours of the target) was used in the Experiment 2: the following letter mask was presented in the same location as that of the first letter target (see Fig. 2). Readers seeking access to the stimuli and codes used in these experiments can download that from the following URL: https://drive.google.com/file/d/1OvWgs2pPra6dW-cCmFtg50NP17DZbBkQ/view?usp=sharing.

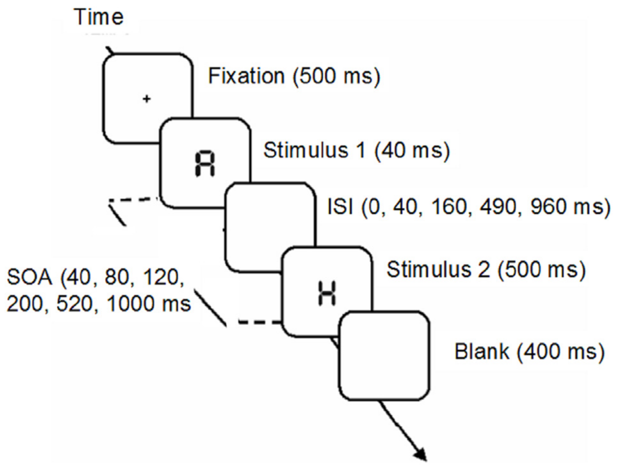

Fig. 2 – Sequence of the visual events during the "Attentional" masking task (Experiment 2).

3. Results

3.1. *Experiment 1 (meta-contrast masking task): group analysis*

The results were fitted by a logistic function for the three groups. The upper bound was set to 1 and the lower bound to $y0 = 0$; $y = 0$ means that the correct letter identification was never properly signaled; $y = 1$ indicates that at a given target-mask SOA, the correct letter identification was always reported. The only free parameters of the function are therefore b (the function slope) and t (the threshold at 50% of correct letter identification). The resulting logistic function (the same as that used previously for other psychophysical tasks by Giora & Gori, 2010; Gori & Spillmann, 2010; Gori & Stubbs, 2006; Gori & Yazdanbakhsh, 2008; Gori et al., 2011; Gori et al., 2015; Ronconi et al., 2012, Yazdanbakhsh & Gori, 2008; 2011) was as follows:

$$y = \frac{1}{1 + e^{-b*(x-t)}}$$

In this equation, x was the target-mask SOA, y the relative response frequency, while the fitting procedure provided the exact function slope and threshold at 50% of correct letter identification for each participant. The mean adjusted-R2 was .98. A univariate analysis of variance (ANOVA) was performed for the thresholds in the meta-contrast masking task, with group as between-participants factor (C, N- and N+). A significant group effect was found ($F_{(2,\,25)} = 9.11$, $p = .001$, $\eta^2_p = .42$), showing that temporal attention engagement of visual events was different among the three groups. Between-participants planned comparisons revealed that the mean threshold was significantly higher (independent-samples *t*-test, $p = .002$) in the N+ (mean = 201 ± 53 msec) compared to both the C (mean = 30 ± 7 msec) and the N- group (mean 50 ± 10 msec; independent-samples *t*-test, $p = .005$; see panel A of Fig. 3). In contrast, mean threshold did not differ between the C and N- group (independent-samples *t*-test, $p = .95$), showing that the delayed temporal attention engagement of an event was specifically associated to left spatial neglect syndrome and not to a generic right-hemisphere lesion. This difference between N+ and N- patients was confirmed also when their age (years), education (years), and time since stroke onset were controlled through a covariate analysis of variance (ANCOVA).

In addition to the mean threshold, another important psychophysical index is the function slope. This index captures the dynamic change of visual perception in a meta-contrast masking paradigm. The equation fitting described above provided the slope for each participant. An ANOVA was performed for the mean slope in the meta-contrast masking task, with group as between-participants factor (C, N- and N+). A significant group effect was found ($F_{(2,\,25)} = 3.36$, $p < .05$, $\eta^2_p = .21$). Between-participants planned comparisons revealed that the mean slope was significantly lower in the N+ group (mean = .01 ±.001) compared to both the C (mean = .38 ±.17, independent-samples *t*-test, $p < .05$) and the N- group (mean = .13 ±.06; independent-samples *t*-test, $p < .05$; see panel B of Fig. 3).

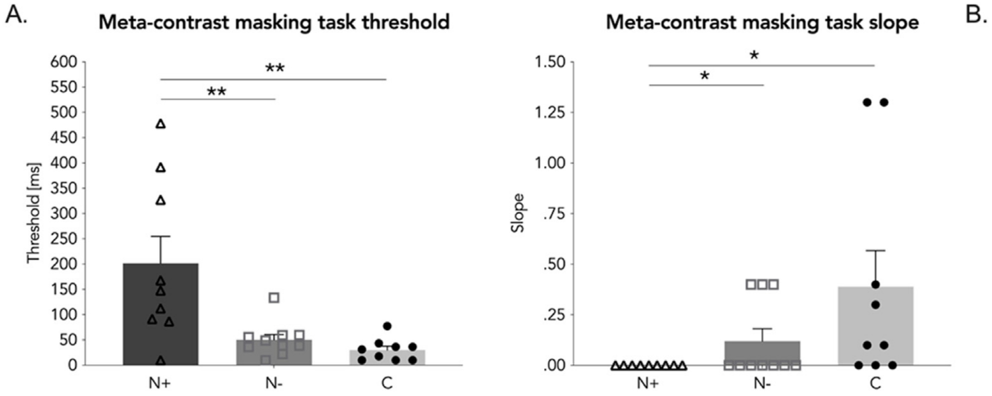

Fig. 3 – Thresholds in ms. (Panel A) and slopes in rate (Panel B) in the three groups of participants (N+ = right-hemisphere stroke patients with left neglect, N- = right-hemisphere stroke patients without left neglect, and C = healthy controls) in the meta-contrast masking task (Experiment 1).

3.2. *Experiment 2 (“Attentional” masking task): groups analysis*

The data of one N- patient was excluded for analysis because target identification was at chance level. Mean target accuracy data at the target-mask SOAs were fitted for each participant with the same logistic function described in the results of the Experiment 1. The mean adjusted-R2 was .98.

ANOVA was performed for the 50% thresholds in the “attentional” masking task, with group as between-participants factor (C, N- and N+). A significant group effect was found ($F_{(2, 24)} = 5.61$, $p = .01$, $\eta^2_p = .32$), confirming that temporal attention engagement of a visual event was different between the three groups. Between-participants planned comparisons revealed that the mean threshold was significantly higher (independent-samples *t*-test, $p = .02$) in the N+ (441 ± 167 msec) compared to both the C (32 ± 15 msec) and N- group (59 ± 11 msec; independent-samples *t*-test, $p = .03$). In contrast, temporal attention engagement of a visual event was not different between the C and the N- group (independent-samples *t*-test, $p > .05$). The difference between N+ and N- right-hemisphere-damaged groups was confirmed also when the chronological age, years of education, and time since stroke were controlled through an ANCOVA (Panel A of Fig. 4).

An ANOVA was performed for the mean slope in the “attentional” masking task, with group as between-participants factor (C, N-, and N+). A significant group effect was found ($F_{(2, 24)} = 5.31$, $p = .01$, $\eta^2_p = .32$). Between-participants planned comparisons revealed that the mean slope was significantly lower (independent-samples *t*-test, $p = .01$) in the N+ (.004 ±.02) compared to the C (.38 ±.11), but not the N- group (.14 ±.06; independent-samples *t*-test, $p > .05$; Panel B of Fig. 4).

Critically, planned comparison at the first target-mask SOA (40 msec) showed that only N+ patients perceive a higher percentage (independent-samples *t*-test, $p = .03$) of the second irrelevant letter (the mask = 69%), rather than first relevant letter (i.e., the target = 31%), showing that the typical temporal priority entry in central vision is not present in left neglect patients.

3.3. *Individual performance analysis*

To quantify the reliability at individual level of these group differences, we used the threshold and slope mean between two experiments (threshold mean between the two experiments: N+ = 321 ± 110 msec; N- = 50 ± 8 msec; C = 31 ± 6 msec. Slope mean between the two experiments: N+ = .007 ±.001; N- =

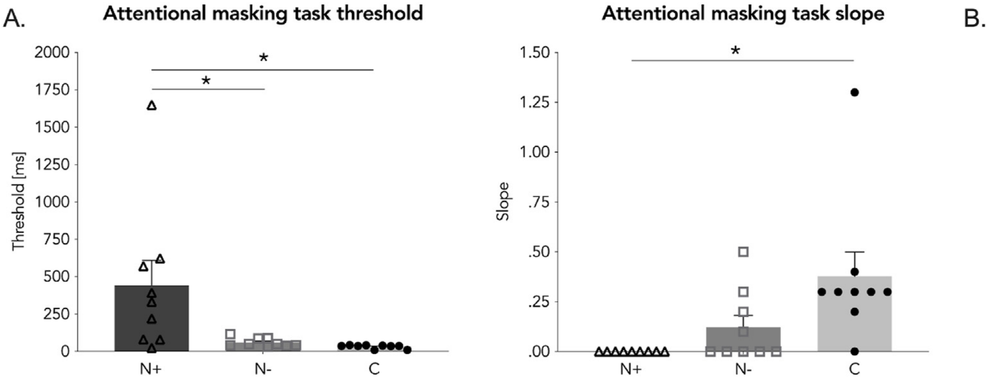

Fig. 4 – Thresholds in ms. (Panel A) and slopes in rate (Panel B) in the three groups of participants (N+ = right-hemisphere-damaged patients with left unilateral neglect, N- = right-hemisphere-damaged patients without left unilateral neglect and C = healthy controls), in the “Attentional” masking task (Experiment 2).

.14 ±.06; C = .38 ±.14). This choice is justified because any difference was found between the three groups across the two experiments (group × experiment interaction: slope: $F_{(1, 24)} = .001$, $p > .05$, $\eta^2_p = < .0001$; threshold $F_{(1, 24)} = 1.79$, $p > .05$, $\eta^2_p = .13$).

We analyzed individual threshold and slope of temporal attention engagement in N+ patients both in comparison to C healthy controls and N- patients. Nine out of nine (100%) N+ patients statistically differed from the C group's mean thresholds, and eight out of nine (89%) statistically differed from the N- group's mean thresholds. In addition, nine out of nine (100%) N+ patients were above the upper bound 95% confidence interval for the mean of the C controls, and eight out of nine (89%) were above the upper bound 95% confidence interval for the mean of the N- patients in the temporal attention engagement. Similar results were found for slope index (100% in comparison to C controls and 100% to N- patients). Thus, individual differences between each single case of N+ patient and the two control groups demonstrate a high reliability of temporal attention engagement deficit in spatial neglect syndrome.

3.4. *Linear regression analysis between temporal attention engagement and spatial attention deficits*

After we established that only patients with left neglect (N+) had shown consistently temporal attention engagement deficits, we further investigated the possible link between individual measures of temporal attention engagement functioning and the typical inability to direct spatial attention toward stimuli on the left side across our entire sample of right-hemisphere patients (n = 19), independently of classical a priori group classification of left spatial neglect syndrome. We used the number of omissions in the left side of the Bell Cancellation test (Gauthier et al., 1989) in which the patient with focal right hemisphere lesion has to search for a specific visual target by rapid sampling of all displayed visual targets or distractor objects.

To determine the predictive relations between temporal attention engagement and the spatial symptom of neglect syndrome in a more stringent way, we computed two two-steps fixed-entry multiple regression analysis in which the dependent variables were: (1) the number of visual target omissions in the left side, and (2) the total number of visual target omissions. To control for the possible confounding effects of age, the predictors entered at the two steps were as follows: (i) chronological age in years, and (ii) mean slope and mean threshold measured in Experiment 1 (i.e., the meta-contrast masking task) and in Experiment 2 (i.e., the "attentional" masking task). Importantly, in the first linear regression analysis, the two measures of temporal attention engagement, entered last, accounted for a large portion of unique variance in left side visual target omissions (r^2 change = .63, F change $_{(2,15)} = 13.82$, $p < .0001$). Consistently, in the second linear regression analysis, the two measures of temporal attention engagement, entered last, accounted for a significant portion of unique variance also in global visual target omissions (r^2 change = .64, F change $_{(2,15)} = 13.92$, $p < .0001$).

We added a further step in our linear regression model because both education and time from stroke are two important clinical variables. The predictors entered at the three steps were as follows: (i) chronological age in years, (ii) years of schooling and days since their stroke, and (iii) mean slope and mean threshold. Confirming the previous analysis, the two measures of temporal attention engagement, entered last, accounted for a significant portion of unique variance in left side visual target omissions (r^2 change = .51, F change $_{(2,13)} = 11.63$, $p < .001$). Consistently, the two measures of temporal attention engagement, entered last, accounted for a significant portion of unique variance also in global visual target omissions (r^2 change = .54, F change $_{(2,13)} = 10.99$, $p < .002$), even if these two clinical factors were controlled for.

These results showed the specific role played by the temporal attention engagement not only on the typical inability to direct spatial attention toward stimuli on the left side, but also on the non-lateralized visual search disorders.

All the data analysis in our studies were performed using SPSS for Window, no analysis code was used.

4. Discussion

Left spatial neglect is characterized by deficits in spatial attention mechanisms of the right hemisphere (Driver & Mattingley, 1998; Vallar, 1998). However, left neglect patients present also other non-spatial attention deficits (for reviews, see Battelli et al., 2007; Corbetta & Shulman, 2011; Husain & Nachev, 2007; Husain & Rorden, 2003; Low et al., 2017).

Some studies have found that the degree of bias in spatial attention is correlated with the effectiveness of non-spatial attention, including vigilance (e.g., Bellgrove et al., 2004; Malhotra et al., 2009; Robertson, et al., 1998), phasic alertness (e.g., Finke et al., 2012; Robertson et al., 1998), attentional capacity (e.g., Bellgrove et al., 2013; Bonato et al., 2010), and temporal attention disengagement (e.g., Husain et al., 1997; Shapiro et al., 2002).

Our findings have shown, specifically, that left neglect patients presented also a delayed temporal attention engagement for central visual events in comparison, not only with healthy individuals, but also with right-hemisphere-damaged patients without neglect.

We measured both meta-contrast (Experiment 1) and "attentional" masking (Experiment 2) in the same participants. These two types of backward masking are measured by simple recognition tasks, in which non-spatial attentional mechanisms are controlled for or at least are minimized. Thus, we showed a temporal attention engagement deficit in left neglect independently from other non-spatial attention abilities, such as phasic alertness, attentional capacity and temporal attention disengagement.

Neglect patients typically show severe phasic alerting disorders. However, pre-stimulus signal presentation is able to significantly reduce patients' spatial attention deficits restoring the efficiency of the right-lateralized alerting system (e.g., Chica et al., 2012; Finke et al., 2012; Robertson et al., 1998; for a review, see Petersen & Posner, 2012). In our experiments, each trial started with an alerting fixation point displayed

500 msec before the target stimulus presentation. This alerting manipulation should nullify or minimize the influence of the possible phasic alerting deficits on participants' performance in our task (e.g., Bertoni, Franceschini, et al., 2024; Kusnir et al., 2011; Ronconi et al., 2016).

Attentional capacity tasks require divided attention where the attentional resources are focused in central vision and a lateralized probe detection is usually combined. Focused attention in the central recognition task allows to measure a left inattention in patients with spatial neglect (e.g., Bonato et al., 2010; Finke et al., 2012) as well as in children with attention deficit hyperactivity disorder (ADHD; e.g., Bellgrove et al., 2013) and developmental dyslexia (e.g., Facoetti et al., 2001; Facoetti & Molteni, 2001; Facoetti & Turatto, 2000; Ruffino et al., 2010). However, our stimuli were always foveal and tested the attentional abilities of right-hemisphere-damaged patients in optimal condition requiring the recognition of solely the first visual event, without any other task in parallel that might have drained attentional resources from the main task.

Temporal attention disengagement is also impaired in patients with left neglect (e.g., Husain et al., 1997; Shapiro et al., 2002). Husain et al. (1997) examined the temporal dynamics of attention in brain damaged patients, through an attentional blink task. Left neglect patients had an abnormally severe and protracted attentional blink, showing a deficit in temporal attentional disengagement. In contrast, our tasks showed that left neglect patients show a temporal attentional deficit, already at the attentional engagement stage. Attentional engagement always precedes the disengagement of attention. Consequently, an impaired attentional engagement could produce a decrease in attentional disengagement performance. In particular, in Experiment 1, left neglect patients were impaired at recognizing the first visual object caused by the successive presentation of lateral masks. This finding suggests the presence of a basic deficit in recognition of salient events embedded in a sequence of non-overlapping events. This deficit for salient events recognition could be caused by a delayed temporal attention engagement, as shown by the results of Experiment 2. In Experiment 2, we found, indeed, that the left neglect patients reported the second event instead of the first event, showing a labile temporal attentional engagement. Before visual target has been identified, the appearance of mask attracts some of the processing resources initially accrued by target, slowing target's identification and increasing the probability that mask will be the first to be identified and hence consolidated (Potter et al., 2002).

Thus, this right temporal attentional network is highly integrated with spatial attentional mechanisms (e.g., Finke et al., 2012; Van Vleet & DeGutis, 2013; for reviews, see Battelli et al., 2007; Corbetta & Shulman, 2002, 2011; Husain & Nachev, 2007; Low et al., 2017) as shown by the high correlation found between temporal attentional engagement performance and the severity of left spatial neglect. Moreover, this deficit of temporal attentional engagement on events was present in all tested neglect patients and successfully predicted the typical left side spatial attentional disorder.

We sustain that our findings are relevant also for clinical issues. It might be assumed that the deficit of temporal attention engagement is linked to an impairment in spatial attention orienting to the left side of space. Future studies could demonstrate a causal link between temporal attention deficit and neglect symptoms. In case this relation would be confirmed, our results suggest that the visuo-spatial deficits in patients with right-hemisphere damage could be reduced by an efficient treatment able to remediate patients' temporal attention engagement performance. Moreover, studies in neglect patients during the acute phase could be interesting in order to better generalize our results to different phases of the neglect syndrome. Finally, neglect syndrome can occur after lesions to other stroke territories beside the area investigated in this study (middle cerebral artery). Previous studies had shown some peculiar behavioral manifestations based on different lesion areas (i.e. posterior cerebral artery, anterior cerebral artery, lateral lenticulostriate arteries; Husain & Kennard, 1997). Consequently, further studies on neglect patients affected by different lesions could be interesting for generalization of our results.

In our study it was not possible to quantitatively measure the stroke severity, it could be interesting, for future studies, to control for stroke severity in order to clarify the impact of a general size of the stroke on the temporal attention deficit.

Previous studies have shown a reduction of the left inattention deficits in unilateral neglect patients by using specific types of training that were able to improve the alerting neural circuit (e.g., Robertson et al., 1998; Van Vleet et al., 2020; Van Vleet & Robertson, 2006). The deficit of temporal attention engagement of visual events might be restored by using action video games training (e.g., Bertoni et al., 2023; 2024a; 2024b; Green & Bavelier, 2003; see Bavelier & Green, 2019; Franceschini et al., 2015 for reviews; see Bediou et al., 2018, 2023; Puccio et al., 2023 for meta-analyses). This specific training is able to improve the recognition of visual objects masked by other successive events (e.g., Franceschini et al., 2013; Li et al., 2010) as well as to reduce attentional blink in healthy participants (e.g., Green & Bavelier, 2003; Oei and Patterson, 2013; Kozhevnikov et al., 2018).

It is important to note, that a very similar disorder of temporal attention engagement is been consistently found also in many neurodevelopmental disorders, such as dyslexia (e.g., de Groot et al., 2015; Facoetti et al., 2008; Laasonen et al., 2012; Ruffino et al., 2010; 2014; Franceschini et al., 2018; Franceschini, Bertoni, & Facoetti, 2021; see Badcock & Kidd, 2015 for a review and meta-analysis), developmental language disorder (e.g., de Groot et al., 2015; Dispaldro et al., 2013), ADHD (e.g., de Groot et al., 2015), and autism spectrum disorder (e.g., Ronconi et al., 2012, 2013, 2014, 2018a, 2018b; 2024; Marsicano et al., 2023).

Interestingly, a left mini-neglect symptom has been shown in dyslexia (e.g., Facoetti et al., 2006; Facoetti & Molteni, 2001; Hari et al., 2001; see Hari & Renvall, 2001 for a review), ADHD (e.g., Sheppard et al., 1999; Stefanatos & Wasserstein, 2001) and autism spectrum disorder (e.g., Bryson et al., 1990; Elsabbagh et al., 2013). Left mini-neglect was defined as a visual attention preference to the right side of space with mild difficulties in orienting attention to the left side of space.

The present findings in left spatial neglect patients suggest that these neurodevelopmental disorders could be linked to similar neuroanatomical mechanisms controlling temporal attention engagement, mediated by the right, stimulus-driven, attentional network to modulate the learning mechanism in developmental stages.

Thus, our evidence could have consequences on the development of innovative rehabilitation programs, not only for the frequent and highly invalidating acquired lesions of the right hemisphere, but also for those neurodevelopmental disorders involving spatial and non-spatial attentional deficits, such as dyslexia (Bertoni et al., 2019, 2021, 2023; 2024; Franceschini & Bertoni, 2019; Franceschini et al., 2013; 2020; 2021; Franceschini et al., 2021; Gori et al., 2016; see Gavril et al., 2021 and Puccio et al., 2023 for meta-analyses), ADHD (Kollins et al., 2020), specific language impairment and autism spectrum disorder (Pitcher & Ungerleider, 2021; Ronconi et al., 2024).

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CRediT authorship contribution statement

Simone Gori: Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Milena Peverelli:** Visualization, Validation, Project administration, Methodology, Investigation. **Sara Bertoni:** Writing – original draft, Validation, Supervision, Methodology, Investigation. **Milena Ruffino:** Methodology, Investigation. **Luca Ronconi:** Methodology, Investigation. **Franco Molteni:** Visualization, Validation, Supervision, Methodology. **Konstantinos Priftis:** Writing – original draft, Visualization, Validation, Supervision. **Andrea Facoetti:** Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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Supplementary data

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