Neuropsychologia 203 (2024) 108975

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Social face processing in chronic severe traumatic brain injury: Altered decoding of emotions and mental states but preserved gaze cueing of attention

Matteo G.F. Vascello [a], Silvia Pizzighello [b], Maria S. Spada [a], Andrea Martinuzzi [b], Mario Dalmaso [c,*]

[a] Clinical Psychology Unit, Papa Giovanni XXIII Hospital, Bergamo, Italy
[b] Scientific Institute IRCCS E. Medea, Conegliano, Treviso, Italy
[c] Department of Developmental and Social Psychology, University of Padova, Padova, Italy

ARTICLE INFO

Keywords:
Traumatic brain injury
Social cognition
Social attention
Gaze cueing
Arrow cueing

ABSTRACT

The processing of social information transmitted by facial stimuli is altered in individuals with traumatic brain injury (TBI). This study investigated whether these alterations also affect the mechanisms underlying the orienting of visual attention in response to eye-gaze signals. TBI patients and a control group of healthy individuals matched on relevant criteria completed a spatial cueing task. In this task, a lateral visual target was presented along with a task-irrelevant face, with the gaze averted to the left or right. Arrows pointing towards the left or right were also used as non-social control stimuli. Social cognition abilities were further investigated through tests based on decoding emotional expressions and mental states conveyed by facial stimuli. The decoding of emotions and mental states was worse in the TBI group than in the control group. However, both groups demonstrated reliable and comparable orienting of attention to both eye-gaze and arrow stimuli. Despite impairments in certain aspects of social face processing among TBI patients, gaze cueing of attention appears to be preserved in this neuropsychological population.

1. Introduction

Traumatic brain injury (TBI) constitutes a critical public health and socio-economic problem worldwide (Peeters et al., 2015). Long-term disability deficits are observed following moderate to severe TBI and include cognitive, neurobehavioural, and psychiatric impairments. The most commonly affected cognitive domains are attention and information processing speed (IPS), memory, and executive functions (Bales et al., 2009). Neurobehavioural symptoms include lack of initiative, impulsivity, irritability, inappropriate social behaviour, and self-centredness (Olver et al., 1996). Psychiatric disorders are also frequently observed, including depression, anxiety, and substance use (Whelan-Goodinson et al., 2009).

Among cognitive sequelae, patients with TBI and their caregivers frequently report complaints about attentional difficulties, suggesting that these aspects could be disruptive in daily life (Van Zomeren & Van den Burg, 1985). The systematic review and meta-analysis conducted by Mathias and Wheaton (2007) provided a comprehensive organisation of the literature on the different types of attention impairments in severe TBI. Specifically, their work highlighted significant deficits in measures of attention span, focused and selective attention, sustained attention, and supervisory attentional control. Of particular interest for the present work are some studies that investigated the orienting of attention employing the spatial cueing task introduced by Posner (1980). In this task, participants respond to a peripheral target while a symbolic cue may appear at the centre of the screen. In healthy individuals, this task generally leads to reliable attentional shifts, with better performance (i.e., shorter latencies and greater accuracy) when the target appears in the same spatial location indicated by the cue (i.e., a congruent trial) compared to when it appears elsewhere (i.e., an incongruent trial; see also, e.g., Galfano et al., 2012; Hommel et al., 2001; Tipples, 2002; for a review and meta-analysis, see Chacón-Candia et al., 2022). However, in TBI patients, the results have been mixed (for reviews and meta-analyses, see Alnawmasi et al., 2022a; Walz et al., 2021), as

* Corresponding author.
E-mail addresses: mvascello@asst-pg23.it (M.G.F. Vascello), silvia.pizzighello@lanostrafamiglia.it (S. Pizzighello), sspada@asst-pg23.it (M.S. Spada), andrea.martinuzzi@lanostrafamiglia.it (A. Martinuzzi), mario.dalmaso@unipd.it (M. Dalmaso).

https://doi.org/10.1016/j.neuropsychologia.2024.108975
Received 3 May 2024; Received in revised form 20 August 2024; Accepted 21 August 2024
Available online 22 August 2024

summarised in the following paragraphs.

On the one hand, in patients with moderate-severe TBI, evidence of impaired attentional orienting can be found in Cremona-Meteyard et al. (1992). Eleven TBI patients and 9 healthy controls were asked to detect a peripheral target while a central arrow, pointing left or right, also appeared. Additionally, a 'neutral' cue (i.e., a cross) which did not provide directional information was also employed to compare performance in the 'neutral' condition with both congruent trials (thus allowing to estimate the so-called 'benefits') and incongruent trials (thus allowing to estimate the so-called 'costs'; see also Posner, 1980). The main findings indicated that TBI patients were overall slower than controls and showed reduced benefits. Moreover, Schmitter-Edgecombe and Kibby (1998) tested 20 TBI patients and 20 healthy controls in a visual search task where a peripheral target appeared among several distractors. They found that TBI patients were overall slower than controls but also that their attention was influenced by the spatial direction of a task-irrelevant central arrow, especially when the target and distractors were perceptively similar. Another work (Kim et al., 2009), using a version of the spatial cueing task, found that 17 TBI patients in the subacute/chronic moderate phase were slower and less accurate than a control group of 15 individuals. Unfortunately, Kim et al. (2009) did not report the behavioural findings about attentional shifting. In the context of mild TBI, Cremona-Meteyard et al. (1994) conducted two experiments with sub-acute to chronic TBI patients ($N = 9$ in Experiment 1, $N = 8$ in Experiment 2) and 12 healthy controls, noting reduced benefits in TBI patients. This pattern was long-lasting, persisting even one year after the injury. More recently, Alnawmasi et al. (2022b) tested 13 individuals with sub-acute to chronic mild TBI and 21 healthy controls, showing that TBI patients responded slower and were insensitive to the central cue.

On the other hand, some studies have reported an overall similar performance between TBI patients and controls. Bate et al. (2001) tested 35 chronic severe TBI patients and 35 healthy controls, asking them to detect a peripheral target presented alongside a central cue (an arrow pointing left or right, or a 'neutral' cross). Although TBI patients were overall slower than controls, there were no significant differences in their ability to orient attention compared to the control group. Similarly, Robertson et al. (2017) tested 30 participants with sub-acute moderate-severe TBI and 30 healthy controls. They found that TBI participants were slower than controls but oriented their attention in response to the arrow cue as the controls did.

It is worth noting that the recent reviews and meta-analyses conducted by Alnawmasi et al. (2022b) and Walz et al. (2021) highlighted significant heterogeneity among studies involving TBI patients. This heterogeneity arises from methodological differences in tasks, such as variations of the Posner task and clinical variability within the tested groups, including differences in sample size, severity of TBI, and stage of recovery (i.e., subacute vs. chronic). These differences might explain the observed discrepancies observed in the studies, where some indicated an impaired orienting response, while others reported no altered performance. Nevertheless, the main findings from the meta-analyses by Alnawmasi et al. (2022b) and Walz et al. (2021) suggest an impairment in spatial cueing of attention in TBI. Specifically, these patients appear not to benefit from congruent trials compared to neutral trials.

1.1. Impaired social cognition in TBI

Increasing evidence proposes that social cognition is also impaired in individuals with moderate to severe TBI. Social cognition refers broadly to the cognitive processes that support flexible behaviour in response to other individuals (Adolphs, 1999). These cognitive processes involve multiple domains and mechanisms, such as emotion perception, understanding of the mental state of others (i.e., the so-called Theory of Mind or ToM) and empathy. Since much of this social information is conveyed through facial expressions, face processing is fundamental to social cognition. Social face processing is commonly impaired in patients with moderate to severe TBI patients, as evidenced by the extensive literature on emotion perception (Babbage et al., 2011; Murphy et al., 2022) and ToM (Muller et al., 2010; Lin et al., 2021). These impairments, in turn, adversely affect social, occupational, and interpersonal functioning in TBI patients (McDonald et al., 2013; Ubukata et al., 2014).

In processing facial stimuli, we are particularly sensitive to the eye-gaze region of others and tend to orient our attention towards the same spatial location they observe (Emery, 2000). This phenomenon, known as 'social attention', is crucial for establishing meaningful connections with others and effectively navigating our environment. For instance, in a face-to-face conversation, quickly understanding where our interlocutor is looking is essential to grasp the meaning of their speech fully and to act appropriately towards an object or location (Capozzi and Ristic, 2018; Dalmaso et al., 2020b; Frischen et al., 2007). A commonly used experimental method to study social attention abilities is the gaze-cueing task (e.g., Driver et al., 1999; Friesen and Kingstone, 1998), derived from Posner task (Posner, 1980). In the gaze-cueing task, participants see a face with an averted gaze at the centre of the screen, followed by a peripheral target requiring a manual response. Performance is generally better (i.e., shorter latencies and greater accuracy) when the target appears in the same spatial location looked at by the facial stimulus, compared to when it appears elsewhere (i.e., a gaze-cueing effect; for a review and meta-analysis, see McKay et al., 2021). Surprisingly, no studies have explored gaze cueing of attention in TBI patients, focusing instead solely on spatial cueing of attention mediated by non-social symbolic cues (see the previous paragraph). Given the documented impairments in social cognition abilities in TBI (McDonald, 2013; Milders, 2019), assessing the ability to orient attention in response to gaze direction may reveal novel insights in this clinical population.

1.2. The present study

The main aim of this study was to investigate social face processing in TBI patients and a control group of healthy participants by focusing on gaze cueing of attention. We employed a gaze-cueing task where a task-irrelevant face, with its gaze directed left or right, was displayed at the centre of the screen. Participants were required to detect a peripheral target by pressing a response key. Additionally, arrow stimuli were employed as an essential control condition, enabling us to contextualise the observed results across social and non-social domains (e.g., Chacón-Candia et al., 2022). We also administered two other tasks to assess the decoding of emotions and mental states conveyed through facial stimuli, commonly used in studies exploring social face processing (e.g., Lin et al., 2021; Murphy et al., 2022).

Regarding decoding emotions and mental states, we expected TBI patients to perform poorer than the control group. More importantly, in alignment with the well-documented impairments in social cognition abilities associated with TBI (e.g., McDonald, 2013), gaze cueing of attention was expected to be compromised in patients but not controls (e.g., McKay et al., 2021). Our hypothesis concerning arrow cueing of attention in TBI was twofold. Given the mixed results from previous studies (see, e.g., Alnawmasi et al., 2022b; Bate et al., 2001; Cremona-Meteyard et al., 1992, see also Alnawmasi et al., 2022a), we posited that TBI patients might exhibit either a compromised or an intact orienting response, while a preserved response was expected in the control group (e.g., Chacón-Candia et al., 2022).

2. Materials and methods

2.1. Participants

The sample size was determined a priori. As we planned to analyse our data with linear mixed-effect models (see the results section), we adhered to the guidelines outlined by Brysbaert and Stevens (2018).

According to these guidelines, a minimum of 1600 observations per experimental condition is recommended. Based on our experimental framework, we concluded that a minimum of 31 participants would be sufficient to meet this requirement.

The experimental group comprised 33 outpatients (25 males, 8 females) with a mean age of 43.7 years ($SD = 11.8$) and a mean education of 9.9 years ($SD = 2.83$). These individuals were recruited from the TBI database of the 'Physical Medicine and Rehabilitation Unit' of the Papa Giovanni XXIII Hospital of Bergamo (Italy). The inclusion criteria were: a severe traumatic brain injury, defined by a score in the Glasgow Coma Scale (GCS) (Teasdale & Jannett, 1974) ≤ 8 ($M = 5.6$, $SD = 2.1$, *range* = 3 to 8) or evidence of post-traumatic amnesia >7 days ($M = 97.1$, $SD = 93.9$, *range* = 12 to 425; see also Stein, 1996); a chronic phase of recovery of at least 1 year after the injury ($M = 5$, $SD = 4.8$, *range* = 1 to 17); fluency in Italian; aged between 18 and 70 years. The exclusion criteria were: a pre-accident history of developmental, neurological, or psychiatric disorders; a history of alcohol or drug dependency; persistent postinjury language deficits or neglect; and motor impairment of the dominant hand. The TBI group had a mean length of Post-Traumatic Amnesia (PTA; Symonds & Russell, 1943) of 97.2 days ($SD = 93.9$). The group was characterised by heterogeneity of traumatic injuries in terms of pathophysiology (contusions, haemorrhages, haematomas, diffuse axonal injury, etc.), and location of brain lesions, documented by CT or MRI scans. Demographic and clinical details are provided in Table 1.

The control group consisted of 33 individuals (25 males, 8 females) with a mean age of 43.6 years ($SD = 12.1$) and a mean education of 10.1 years ($SD = 2.9$). They were recruited from among the friends and family members of the Physical Medicine and Rehabilitation Unit staff. The exclusion criterion was a positive history of developmental, neurological, or psychiatric disorders. There were no significant differences between the TBI and control groups regarding age ($p = .96$) and years of education ($p = .83$).

To describe the cognitive and psychological profile of our patients and healthy controls, we administered a battery of standardised neuropsychological tests and a self-report measure of mood/anxiety (details in the following paragraph). All participants provided their informed written consent. The study was approved by the Papa Giovanni XXIII Hospital of Bergamo Ethics Committee (prot.n.: REG. SPERIM.N.50/18) and was conducted following the guidelines of the Declaration of Helsinki.

2.2. Neuropsychological and psychological profile measures

In a first phase, we collected information to determine the neuropsychological and psychological profile of each participant. We also administered two additional tests to assess relevant aspects of social cognition abilities (i.e., the recognition of facial expressions and ToM).

2.2.1. Neuropsychological profile

A battery of standardised neuropsychological tests was administered to both TBI patients and the control group to measure: A) IPS, B) memory, and C) attention/executive functioning. For the sake of brevity, a detailed list of the adopted tests is reported in the 'Supplementary Material' document.

Table 1
Demographic and clinical features of participants with traumatic brain injuries.

ID	Age	Education	Gender	Length of PTA (days)	GCS	Since Injury	Cause of TBI	Damage reported on acute phase CT/MRI scan
1	56	8	F	12	8	2	MVA	Contusions Bilat F lobes
2	26	11	M	81	5	4	MVA	Contusions Bilat F + R T lobes, R BG, L Thalamus, L Corpus Callosum; DAI
3	45	8	M	65	8	2	MVA	SAH, Contusions Bilat F + R T lobes
4	36	8	M	147	3	17	MVA	Diffuse Edema, EDH L and R, Contusion R F lobe
5	25	8	M	51	5	3	MVA Ped	SAH, R SDH, Contusions R T + Bilat F lobes
6	44	8	M	13	8	3	MVA	ICH, Contusions bilat F + L Thalamus
7	63	13	M	95	7	5	MVA	SAH, Contusions Bilat F + L T + R P lobes
8	57	8	M	25	8	3	MVA	SAH, Contusions R F-T + R O + L P lobes
9	35	11	M	84	4	15	MVA	Diffuse Edema, L EDH P-O lobes, Contusions Bilat F-T-P lobes + L Cerebellum, R BG
10	50	8	M	27	8	2	MVA	Contusions Bilat F + LT lobes
11	23	8	M	55	3	2	MVA	SAH, L SDH, Contusions Bilat F + L T lobes
12	46	13	M	17	7	2	Fall	SAH, SDH L T lobe, Contusions Bilat F + R T lobes
13	36	13	M	71	5	14	MVA	R Hemispheric Edema, Contusions F-T lobes, R BG
14	54	8	M	172	3	9	MVA	Extensive Contusions Bilat F-T lobes
15	35	8	M	142	4	7	MVA	EDH L F-T, Contusions Bilat F + L T lobes
16	58	8	F	32	8	2	FALL	SAH, Contusion L P lobe; DAI
17	52	8	M	49	8	4	FALL	Contusions L F-T-P lobes
18	46	13	M	134	5	1	MVA	SAH, Contusions Bilat F lobes, L thalamus, Corpus Callosum; DAI
19	63	5	M	34	3	3	FALL	L P-O SDH, Contusion L F lobe
20	49	13	M	74	3	2	MVA	Diffuse edema, Contusions Bilat F -T; DAI
21	41	8	M	118	6	8	MVA	SDH Bilat F lobes, Contusions R F lobes, Corpus Callosum, R thalamus; DAI
22	57	8	M	59	8	5	MVA	R T SDH, Contusions Bilat F-T + L T-O lobes
23	42	13	F	131	3	1	MVA	SAH, L SDH, Contusions L F-T lobes
24	22	13	F	425	5	2	MVA	SAH, Contusions Bilat F-T lobes, L internal capsule, Corpus callosum; DAI
25	46	8	M	22	7	5	FALL	Diffuse edema, SAH, Contusions Bilat F lobes, SDH Bilat O
26	40	8	M	35	4	3	FALL	R Hemispheric Edema, Contusions L F-T-P + R T lobes
27	26	13	F	113	4	1	MVA Ped	L EDH, R BG, Contusions Bilat F-T lobes, Corpus Callosum; DAI
28	48	13	M	228	6	2	MVA	Contusions R F + L T lobes, R thalamus, Corpus Callosum; DAI
29	34	8	M	27	8	2	MVA	SAH, Contusions Bilat T + R P lobes
30	40	18	F	82	3	17	MVA	SAH, Contusion Bilat F-T lobes, Corpus Callosum; DAI
31	36	13	F	339	8	2	MVA	SAH, Contusions Bilat F + R T Lobes, Corpus Callosum; DAI
32	49	8	M	225	3	12	MVA	Diffuse edema, Bilat F-T + L O lobes; DAI
33	63	8	F	23	8	2	MVA	SAH, Contusions L T + R F lobes, L thalamus

Note. PTA: posttraumatic amnesia, GCS: Glasgow Coma Scale; M: male; F: female; MVA; motor vehicle accident; MVA Ped: motor vehicle accident as pedestrian; SRHI: sports-related head injury; CT: computed tomography; MRI: magnetic resonance imaging; ICH: intracerebral hemorrhage; SAH: subarachnoid hemorrhage; SDH: subdural hematoma, EDH: extradural hematoma; DAI: diffuse axonal injury; R: right; L: left; Bilat: bilateral; F: frontal; P: parietal; T: temporal; O: occipital; BG: basal ganglia; N/A: not available.

2.2.2. Psychological profile

To assess the emotional distress of TBI patients, we used the Hospital Anxiety and Depression Scale (HADS; Zigmond and Snaith, 1983), which is a brief self-report scale. HADS measures symptoms of depression (HADS-D) and anxiety (HADS-A) over the past week using two scales, each comprising seven items scored on a 4-point Likert scale ranging from 0 to 3. The literature provides evidence for its use following TBI (e.g., Dahm et al., 2013).

2.2.3. Social cognition tasks

The two tests were administered using a 15-inch laptop computer with E-Prime software (Psychology Software Tools, Pittsburgh, PA). Emotional facial expression recognition was assessed through an experimental task created ad-hoc, hereafter referred to as the 'Emotional Recognition Task' (ERT). We utilised stimuli from the validated and freely available Radboud Faces Database (Langner et al., 2010). A sample of 42 full-colour photos of adult Caucasians (10.9° width × 11.4° height), balanced for gender (i.e., half female, half male), was selected. For each of the six basic emotions (anger, sadness, fear, disgust, surprise, happiness)—the most consistently recognised across cultures (Ekman, 1992)—we selected a total of 6 examples. In addition, we included a neutral expression. Each expression was presented with a direct gaze against a uniform white background. The models wore black T-shirts, had no hair covering parts of their faces, and wore no glasses, makeup, or jewellery. Each face was presented centrally in a random order. Participants were asked to select the emotion that best described the facial expression from seven labels, which appeared on the computer screen below the face in a fixed position. Responses were recorded via the laptop trackpad. The test was untimed, allowing participants to take as long as they wished to identify the emotion. Two practice trials were conducted before the main task, which lasted approximately 10 min.

The test assessing ToM was the Reading the Mind in the Eyes (RME) test (Baron-Cohen et al., 2001). During the RME, participants were presented with 20 photographs of human eyes (16.5° width × 7° height) and asked to select which of four simultaneously presented labels best described the mental state of the depicted person (e.g., bored, comforting). Each photograph was displayed alone at the centre of the screen, with the four labels appearing near each of the four edges of the picture. A glossary was available if participants were unsure of the meaning of a word. Responses were recorded via the laptop trackpad, with no time limits. The RME test is considered a reliable ToM assessment for several reasons. First, it exclusively features complex mental states to increase variability in performance. Second, it requires participants to select the most appropriate word from four options, clarifying what the person in the picture is thinking or feeling, thus maximising the potential to reveal individual differences in performance. Third, the distractor words for mental states are closely matched with the emotional valence of the target word, enhancing the ability to detect subtle differences in performance.

To account for possible impairments in face perception, we also administered the Benton Facial Recognition Test (BFRT; Benton et al., 1983). In more detail, participants were required to match a target face with one of six photographs, beginning with more straightforward front-view photos and progressing to more challenging angles and lighting conditions. Depending on their performance, they completed either a short (13 trials) or full (22 trials) test version, with accuracy scores standardised for comparison.

2.3. Spatial cueing task

The second phase consisted of a behavioural task based on a version of the spatial cueing paradigm proposed by Posner (1980), in which both social and non-social stimuli served as task-irrelevant spatial cues.

The test was administered using the same laptop and software as the previous tasks. Participants were seated approximately 60 cm away from the laptop. Manual responses were collected via the computer keyboard. The screen background was set to black. Face and arrow stimuli matched those used in previous research on social attention (Dalmaso et al., 2020a, 2020c, 2022). Specifically, the face stimulus was a female avatar face (9.5° width × 12.5° height) created with DAZ 3D software (https://www.daz3d.com). Three versions of this face were used: one with a direct gaze, one with the gaze averted to the left, and another with the gaze averted to the right. Using an avatar face offers the main advantage of providing participants with a well-controlled stimulus while maintaining adequate ecological validity. The arrow stimuli consisted of two white arrows directed either leftward or rightward. The two arrows covered the same area (i.e., 1.3° width × 1° height) as the avatar eye region.

Face and arrow stimuli were presented within two distinct blocks, which were selected in a counterbalanced manner among the participants. Each trial began with a white fixation cross (.5°) displayed in the centre of the screen (Fig. 1, fixation cross frame). The fixation cross remained visible for the duration of the trial. After 600 ms, depending on the block, the face with a direct gaze or the two arrows without the head was presented centrally for 900 ms (Fig. 1, pre-cue stimulus). Then, the two arrows pointing leftwards or rightwards, or the face with the gaze averted leftwards or rightwards, were presented centrally for 200 ms (Fig. 1, cue stimulus). Finally, a target (i.e., a white circle; 1.1° in diameter) could appear 13° leftward or rightward from the centre of the screen (Fig. 1, cue and target stimuli frame). The spatial location of the target was not related to that indicated by the central cue (i.e., they matched only in 50% of the trials). Participants were instructed to look at the centre of the screen throughout the trial and to detect the target as quickly and accurately as possible by pressing the spacebar key. They were also instructed to ignore the spatial direction indicated by the central cue, as it was unrelated to the spatial location of the upcoming target. On some trials (i.e., catch trials), the target did not appear, and no manual response was required. Catch trials were included primarily to maintain participants' focus on the task. For an incorrect or missing response, visual feedback (i.e., the words 'ERROR' or 'MISSING RESPONSE', respectively) was displayed centrally for 1000 ms. A final blank screen appeared for 1000 ms, providing the participant time to prepare for the next trial.

For each type of stimulus (i.e., face and arrow), there was a practice block consisting of 8 target-present trials and 2 catch trials, followed by an experimental block comprising 104 target-present trials and 26 catch trials. Thus, each participant completed 260 experimental trials (i.e., 52 data points per experimental condition). Within the two experimental blocks, each condition was presented an equal number of times and selected randomly.

3. Results

3.1. Neuropsychological, psychological, and social cognition measures

The neuropsychological profile of healthy controls fell entirely within the range of normality, as did that of the TBI patients, except for a borderline performance on memory tasks (i.e., RAVLT). Moreover, TBI patients performed worse than healthy controls on all tests except the Wisconsin D and HADS A. All results are reported in Table S1.

The BFRT revealed no face perception impairments in either group—i.e., all scores felt within the 43–52 range ($M = 47$, $SD = 2.8$) for TBI, and the 43–53 range ($M = 48.3$, $SD = 3$) for the healthy controls—and the difference in performance between them was not significant ($p = .066$). The other tasks aimed at assessing social cognition confirmed worse performance in TBI patients compared to the control group. Specifically, as for the ERT, the percentage of wrong responses was higher in TBI patients ($M = 47.6\%$, $SE = 1.6$) than in the control group ($M = 31.2\%$, $SE = 1.5$; $t(32) = 6.68$, $p < .001$, $d = 1.16$). A similar pattern emerged for the RME test, with TBI patients showing more errors ($M = 47.9\%$, $SE = 1.8$) than the control group ($M = 34\%$, $SE = 2.3$; $t(32) = 4.73$, $p < .001$, $d = .82$).

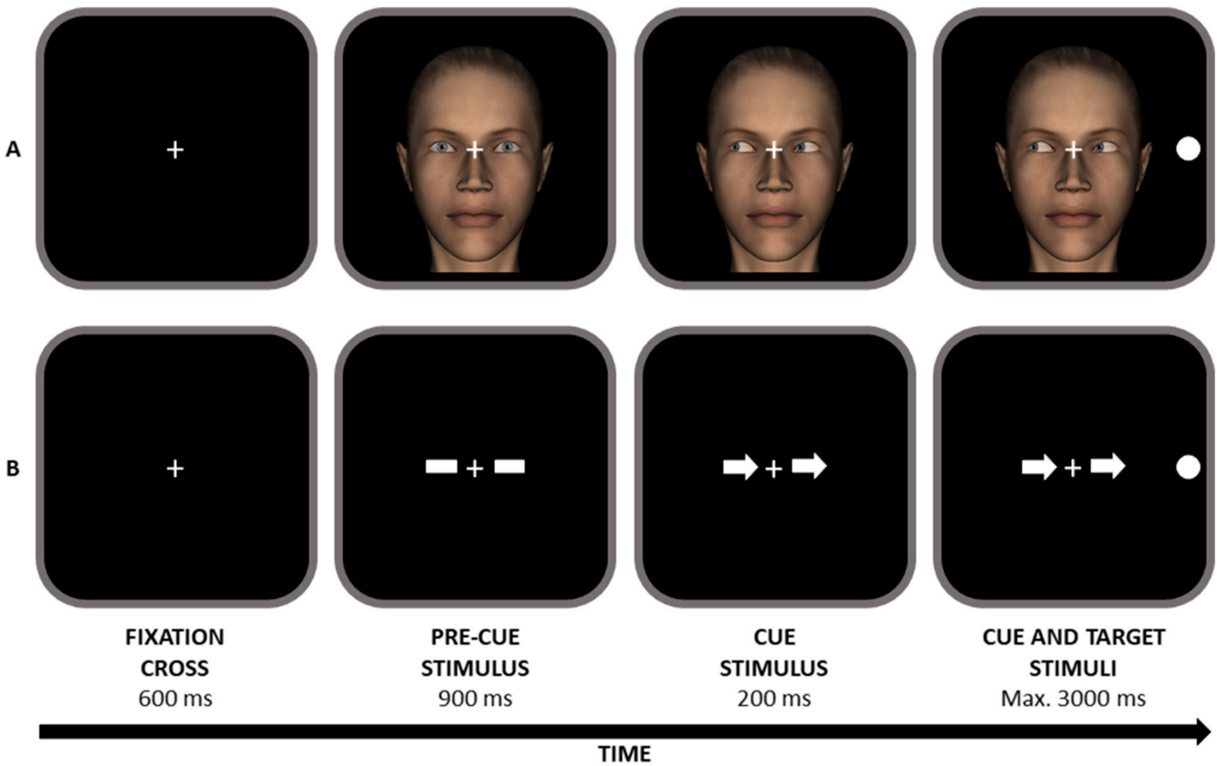

Fig. 1. Examples of trials and stimuli (not drawn to scale) used in the experiment. Panel A depicts an incongruent trial, where the face looks left, and the target appears on the right. Panel B depicts a congruent trial, where the arrow points to the right, and the target appears on the right.

3.2. Spatial cueing task

3.2.1. 3.2.1. data handling

Responses on catch trials (i.e., false alarms) were rare (1.57% of trials), and were therefore discarded and not further analysed. Similarly, for target-present trials, missing responses, which were also rare (.15% of trials), were discarded and not further analysed. Trials correctly responded to but with a latency shorter than 100 ms or greater than 3 standard deviations (SD) from the participant's mean, calculated separately for each experimental condition, were considered outliers (1.08% of trials) and excluded from the analyses.

3.2.2. Analyses of RTs

The latencies of correctly responded trials were analysed using a linear mixed-effects model with the 'lme4′ library (Bates et al., 2015) in R software (https://cran.r-project.org). A minimum of 1682 trials was observed in each experimental cell, thus ensuring sufficient power. Different models (ranging from null to saturated) were compared using the 'MuMin' library (Burnham and Anderson, 2002). The model that best fit our data included Congruency (2 levels: congruent vs. incongruent), Cue (2 levels: gaze vs. arrow), and Group (2 levels: TBI vs. control) as fixed effects, and the intercept for participants and the by-participant slope for Cue as random effects. Standard effect sizes were calculated to directly compare with previous studies assessing the orienting of attention in TBI.

The main effect of Congruency was significant, $F(1, 13387) = 103.666$, $p < .001$, $\eta_g^2 = .011$, due to smaller latencies on congruent trials ($M = 382$ ms, $SE = 10.5$) than on incongruent trials ($M = 401$ ms, $SE = 10.5$), as well as the main effect of Cue, $F(1, 64) = 14.162$, $p < .001$, $\eta_g^2 = .018$, due to smaller latencies in response to gaze stimuli ($M = 380$ ms, $SE = 10.5$) than in response to arrow stimuli ($M = 404$ ms, $SE = 11.4$). The main effect of Group was also significant, $F(1, 64) = 50.049$, $p < .001$, $\eta_g^2 = .414$, due to smaller latencies in the control group ($M = 318$ ms, $SE = 14.8$) than in the TBI group ($M = 466$ ms, $SE = 14.8$[1]). The interaction involving Congruency and Group was also significant, $F(1, 13385) = 5.533$, $p = .019$, $\eta_g^2 = .0006$. This was further analysed by comparing congruent and incongruent trials separately for each group using the 'lsmeans' library (Lenth, 2016). The results indicated that both groups responded faster on congruent than incongruent trials ($ps < .001$). Still, the difference between congruent and incongruent trials was greater in the TBI group (23.3 ms) than in the control group (14.6 ms). All other interactions were non-significant (i.e., Congruency × Cue, $p = .782$; Cue × Group, $p = .077$), including the theoretically relevant

[1] TBI patients were slower than healthy controls overall. This is consistent with previous studies on attentional mechanisms in this clinical population (e.g., Bate et al., 2001; Cremona-Meteyard et al., 1992; Robertson et al., 2017). However, comparing the performance of two groups with large differences in overall RTs can be problematic. To address this issue, we conducted additional analyses by computing proportional RTs (see also, e.g., Aranda-Martín et al., 2022; Bialystok et al., 2008; Colcombe et al., 2005). These analyses showed that the interaction between Congruency and Group was non-significant ($p = .476$), as well as the theoretically relevant three-way interaction ($p = .733$). The only significant results were the main effects of Congruency and Cue ($ps < .001$).

three-way interaction of Congruency × Cue × Group ($p = .847$[2]; see also Fig. 2).

Bayesian analyses were also computed. We used the 'bayestestR' library. These analyses provided strong evidence ($BF_{10} > 150$) for the model including the factors Congruency and Group (and their interaction), over the model including three factors Congruency, Cue and Group (and their interactions).

4. Discussion and conclusions

Moderate to severe TBI is often characterised by deficits in social face processing, including the perception of emotions and ToM (Lin et al., 2021; Murphy et al., 2022). These deficits may contribute to difficulties in social behaviour and lead to unfavourable social outcomes (Milders, 2019). In social face processing, social attention is a crucial phenomenon elicited by gaze cues (e.g., Emery, 2000). Surprisingly, so far, no studies have examined social attention in individuals with TBI. In the current study, we first investigated whether the documented impairments in social face processing in TBI patients may also extend to the mechanisms governing social attention. The main results can be summarised as follows.

First, regarding emotion perception and ToM (i.e., the ERT and RME tasks), TBI patients performed worse than healthy controls in terms of accuracy. This suggests a difficulty in TBI patients in processing social cues, as already documented in previous evidence (e.g., Lin et al., 2021; Murphy et al., 2022). Second, in the spatial cueing task, we observed a significant main effect of group, with TBI patients being overall slower than healthy controls. This aligns with most studies investigating the orienting of attention (as well as other cognitive mechanisms) in TBI (e.g., Bate et al., 2001; Robertson et al., 2017). This is also consistent with the IPS reduction in TBI (e.g., Mathias and Wheaton, 2007). The main effect of cue type was also significant, with responses being faster for the face stimulus than for the arrow stimulus. This is consistent with some previous studies reporting a similar difference between the two categories of stimuli (see, e.g., Kuhn et al., 2010; Quadflieg et al., 2004). According to some authors, this may indicate that facial stimuli can enhance the arousal levels in observers, thereby leading to a quicker response to targets (e.g., Hietanen et al., 2016, 2018). Furthermore, we observed an interaction between congruency and group: both TBI and healthy controls showed a reliable cueing of attention, but the overall magnitude of this phenomenon was greater in the former case. This result was unexpected and, to our knowledge, has not been documented before in TBI patients. It is worth noting that a similar pattern emerged in a recent study including neuropsychological patients (i.e., brain-damaged patients with unilateral spatial neglect; Narison et al., 2020), where the clinical group showed a greater attentional orienting than the control group of healthy individuals. According to the authors (see Narison et al., 2020), this could be attributable to compensatory mechanisms implemented by brain-damaged patients to overcome potential attentional difficulties. However, it is important to note that the interaction between congruency and group did not persist in control analyses based on proportional RTs (see Footnote 1). Therefore, this result should be interpreted with caution and further addressed in future studies. Finally, and most importantly for our hypotheses, the three-way interaction involving congruency, cue type, and group was not statistically significant. This indicates that the attentional responses elicited by the two cue types were similar in both groups.

The findings emerging from this work are important for three main reasons. Firstly, they corroborated the conclusions of some previous works (Bate et al., 2001; Robertson et al., 2017) in which reliable attentional responses to arrow cues have been documented in TBI patients. Secondly, and contrary to our hypotheses, they suggest that social attention could be preserved in TBI patients despite the impairments observed in other components of social face processing (i.e., ERT and RME tasks). Thirdly, the observed similarities in how gaze and arrow cues influence attentional orienting align with findings from a broad spectrum of prior research (see Chacón-Candia et al., 2022, for a review and meta-analysis). This could imply that the neurocognitive mechanisms governing the orienting responses to both cues could overlap, at least to some extent (e.g., Callejas et al., 2014). The main results emerging from the current study suggest that while TBI individuals may show impairments in specific components of social face processing (in our case, emotion perception and ToM), their ability to orient to eye-gaze stimuli appeared intact. This could be interpreted as further supporting evidence that social attention, unlike other mechanisms supporting social cognition, may be considered a hard-wired ability deeply rooted in human cognition, as documented by several studies coming from developmental and even comparative psychology (e.g., Reid et al., 2017; Shepherd, 2010; Zeiträg et al., 2022).

The present work fits into a rather substantial body of literature exploring gaze-mediated orienting of attention in neuropsychological patients. These include patients with cerebrovascular diseases or brain tumours (Akiyama et al., 2006, 2007; Vecera and Rizzo, 2004, 2006), as well as split-brain patients (Kingstone et al., 1998), and right hemisphere-damaged patients with unilateral spatial neglect (Vuilleumier, 2002; Bonato et al., 2009; Narison et al., 2020, 2021; see also Dalmaso et al., 2015). In some cases, gaze-mediated orienting appeared to be compromised, primarily when brain damages were confined to specific brain regions known to be involved in eye-gaze processing and social attention (see, e.g., Stephenson et al., 2021), such as frontal lobes (Vecera and Rizzo, 2004, 2006), the superior temporal gyrus (Akiyama et al., 2006), and the amygdala (Akiyama et al., 2007). In other cases, a spared gaze-mediated orienting has also been reported (e.g., Dalmaso et al., 2015; Kingstone et al., 1998; Vuilleumier, 2002). In the context of the present study, it is probable that in patients with severe TBI, where there is a high level of heterogeneity of lesion patterns among the individuals (e.g., Bigler, 2013; Sharp et al., 2014), the mechanisms underlying social attention may be less compromised, compared to brain pathologies that involve certain brain areas in a more focal way (Ferrell and Tanev, 2002; Zhang et al., 2016). Nevertheless, many factors should be considered to fully grasp the origins of these differences. These range from the severity of brain damage and the affected brain parts to more practical aspects such as the type of faces used in the studies (for example, simple drawings of faces vs. more lifelike faces). The fact that gaze-mediated orienting can emerge even in brain damage of various natures may further prove the existence of a relatively broad neural architecture underpinning social attention involving both cortical and subcortical areas (e.g., Stephenson et al., 2021).

This study represents the first attempt to explore social attention in patients with TBI. Consequently, numerous avenues warrant exploration in upcoming research. For instance, future studies using different experimental procedures could question the similarity between gaze and arrow observed here. Indeed, while evidence suggests that gaze and arrow cues used in cueing tasks similar to the one employed here can elicit different orienting responses in clinical populations characterized by deficits in social cognition (e.g., autism spectrum disorder, Senju et al., 2004; ADHD, Marotta et al., 2017; schizophrenia, Dalmaso et al.,

[2] As suggested by a reviewer, we conducted exploratory analyses and identified five TBI patients (ID: 7, 12, 17, 19, and 20; see Table 1) whose mean RTs may indicate impaired gaze-cueing of attention. From a neuropsychological perspective, these patients exhibited considerable heterogeneity in brain lesion patterns, which is typical in TBI (e.g., Bigler, 2013; Sharp et al., 2014). However, some of the lesioned brain areas in this subgroup are known to be involved in social attention mechanisms, such as the frontal, temporal, and parietal lobes (see, e.g., Stephenson et al., 2021). Although this could explain the poor performance in orienting to eye-gaze stimuli, the overlapping of these lesion sites with those observed in most of the whole TBI sample, the limited size of the subgroup, and the lack of fine-grained neuroimaging techniques (e.g., Diffusion Tensor Imaging) make it difficult to draw definitive conclusions.

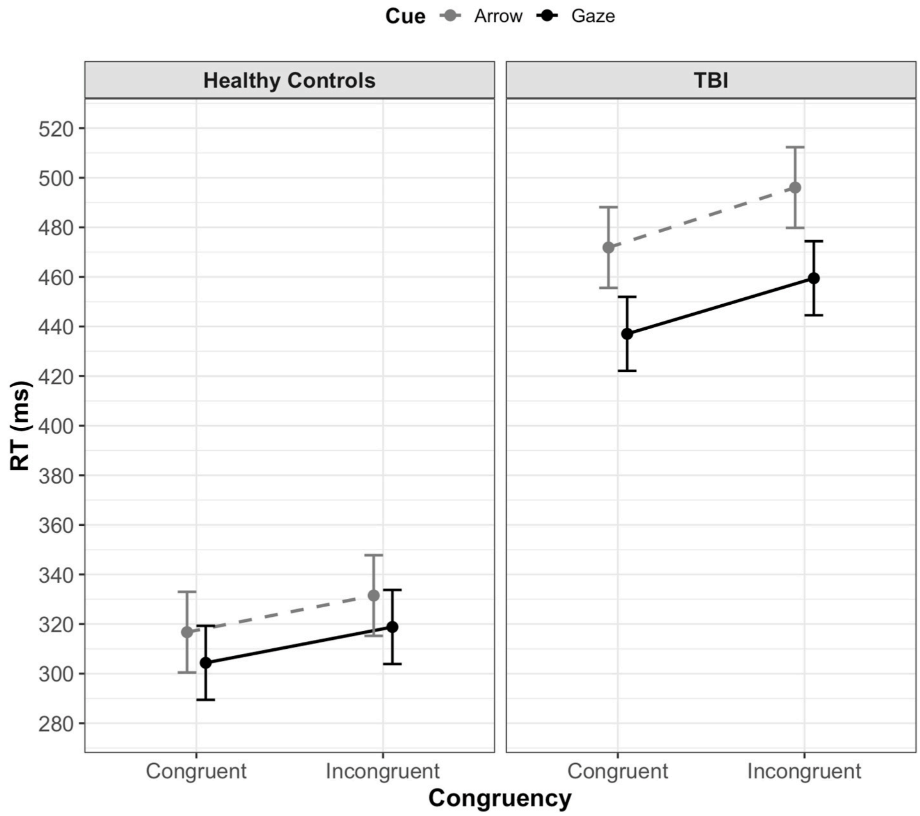

Fig. 2. Mean RT (in ms), observed in healthy controls and TBI, for spatially congruent and incongruent trials as a function of cue type. Error bars are SEM.

2013) compared to healthy controls, other tasks may be more effective in dissociating the attentional processes involved in social versus non-social orienting. For instance, Marotta et al. (2012) used eye gaze and arrow cues while congruent and incongruent targets could appear inside the same or a different object. The results showed location-specific cueing effects for gazes and object-specific cueing effects for arrows. In addition, in Cañadas and Lupiáñez (2012) and Román-Caballero et al. (2021) eye-gaze and arrow stimuli were used as targets in a spatial Stroop task. The main results showed that while a standard spatial Stroop task emerged for arrows—i.e., participants were faster when the direction of the arrow and its spatial location on the screen were identical (e.g., left-left) than dissimilar (e.g., left-right)—the opposite result emerged for eye-gaze. These examples offer intriguing avenues for advancing research in social and non-social attention in TBI.

Another prospective avenue involves recording eye movements, as they offer a more direct, ecologically valid, and sensitive means of measuring attentional responses to social and non-social stimuli (e.g., Dalmaso, 2022; Kristjánsson, 2011). Moreover, given the well-documented difficulties TBI patients encounter when dealing with emotional stimuli, subsequent studies could use tasks involving gaze-mediated orienting of attention with diverse facial expressions, as they have the potential to distinctively shape the social attention response (for a review, see Dalmaso et al., 2020b). Furthermore, there is room for investigating other attentional mechanisms, such as the 'attention holding' effect, characterised by a delayed response in disengaging attention from a specific central stimulus compared to another. For example, Georgiou et al. (2005) reported that anxious individuals exhibited slower disengagement from a central face, displaying a negative emotion compared to a positive one. This would contribute to a broader understanding of the mechanisms underlying social attention in TBI patients. A final consideration pertains to the composition of our experimental sample and, consequently, the control group, which consisted of a higher number of males ($N = 25$) compared to females ($N = 8$). This imbalance was expected and practically unavoidable, aligning with numerous epidemiological studies (e.g., Frost et al., 2013) that consistently demonstrate a higher incidence of TBI in males than in females. Given the documented evidence indicating potential sex differences in tasks assessing the orienting of attention to central cues (with males potentially being less sensitive to central cues in general; see, e.g., Bayliss et al., 2005), we recommend that future studies strive to include an equal representation of both male and female TBI patients. Of course, this suggestion acknowledges the challenges in finding female TBI patients but aims to enhance the overall comprehensiveness of research in this domain.

In summary, this study explored social face processing in patients with chronic severe TBI and found that these patients, when compared to a control group of healthy individuals, exhibited poorer performance in distinguishing emotional expressions and intentions from facial stimuli. However, their ability to orient attention in response to averted eye-gaze and arrow stimuli was comparable to that of the healthy group. These findings offer new insights into the functioning of social cognition and social attention within the TBI clinical population.

Funding details

This work was supported by the 'Ministero Italiano dell'Università e della Ricerca' under the grant 'Prin (2022) PNRR (P2022TPX8E)' awarded to MD, by the 'Ministero Italiano della Salute' under the grant 'Ricerca Corrente 2024' awarded to AM, and by the '5 per mille' funds for biomedical research awarded to SP.

CRediT authorship contribution statement

Matteo G.F. Vascello: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Silvia Pizzighello:** Writing – review & editing, Writing – original draft, Funding acquisition. **Maria S. Spada:**

Writing – review & editing, Supervision. **Andrea Martinuzzi:** Writing – review & editing, Supervision, Funding acquisition. **Mario Dalmaso:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare there are no competing interests to declare.

Data availability

Data, stimuli, and codes can be found here: https://doi.org/10.17605/OSF.IO/DQGB8

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2024.108975.

References

Adolphs, R., 1999. Social cognition and the human brain. Trends in Cognitive Science 3 (12), 469–479. https://doi.org/10.1016/s1364-6613(99)01399-6.

Alnawmasi, M.M., Mani, R., Khuu, S.K., 2022a. Changes in the components of visual attention following traumatic brain injury: a systematic review and meta-analysis. PLoS One 9 (6), e0268951. https://doi.org/10.1371/journal.pone.0268951, 17.

Alnawmasi, M.M., Walz, J.A., Khuu, S.K., 2022b. Deficits in visuospatial attentional cueing following mild traumatic brain injury. Neuropsychologia 177, 108422. https://doi.org/10.1016/j.neuropsychologia.2022.108422.

Akiyama, T., Kato, M., Muramatsu, T., Saito, F., Umeda, S., Kashima, H., 2006. Gaze but not arrows: a dissociative impairment after right superior temporal gyrus damage. Neuropsychologia 44 (10), 1804–1810. https://doi.org/10.1016/j.neuropsychologia.2006.03.007.

Akiyama, T., Kato, M., Muramatsu, T., Umeda, S., Saito, F., Kashima, H., 2007. Unilateral amygdala lesions hamper attentional orienting triggered by gaze direction. Cerebr. Cortex 17 (11), 2593–2600. https://doi.org/10.1093/cercor/bhl166.

Aranda-Martín, B., Ballesteros-Duperón, M.Á., Lupiáñez, J., 2022. What gaze adds to arrows: changes in attentional response to gaze versus arrows in childhood and adolescence. Br. J. Psychol. 113, 718–738. https://doi.org/10.1111/bjop.12552.

Babbage, D.R., Yim, J., Zupan, B., Neumann, D., Tomita, M.R., Willer, B., 2011. Meta-analysis of facial affect recognition difficulties after traumatic brain injury. Neuropsychology 25 (3), 277–285. https://doi.org/10.1037/a0021908.

Bales, J.W., Wagner, A.K., Kline, A.E., Dixon, C.E., 2009. Persistent cognitive dysfunction after traumatic brain injury: a dopamine hypothesis. Neuroscience and Biobehavioural Reviews 33 (7), 981–1003. https://doi.org/10.1016/j.neubiorev.2009.03.011.

Baron-Cohen, S., Wheelwright, S., Hill, J., Raste, Y., Plumb, I., 2001. The 'Reading the Mind in the Eyes' Test revised version: a study with normal adults, and adults with Asperger syndrome or high-functioning autism. J. Child Psychol. Psychiatry Allied Discip. 42 (2), 241–251. https://doi.org/10.1111/1469-7610.00715.

Bate, A.J., Mathias, J.L., Crawford, J.R., 2001. The covert orienting of visual attention following severe traumatic brain injury. J. Clin. Exp. Neuropsychol. 23 (3), 386–398. https://doi.org/10.1076/jcen.23.3.386.1190.

Bates, D., Mächler, M., Bolker, B.M., Walker, S.C., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Software 67 (1). https://doi.org/10.18637/jss.v067.i01.

Bayliss, A.P., Di Pellegrino, G., Tipper, S.P., 2005. Sex differences in eye gaze and symbolic cueing of attention. Q. J. Exp. Psychol. 58 (4), 631–650. https://doi.org/10.1080/02724980443000124.

Benton, A.L., Sivan, A.B., Hamsher, K.D.S., Varney, N.R., Spreen, O., 1983. Facial recognition: stimulus and multiple choice pictures. In: Benton, A.L., Sivan, A.B., Hamsher, K.D.S., Varney, N.R., Spreen, O. (Eds.), Contribution to Neuropsychological Assessment. Oxford University Press, New York, NY, pp. 30–40.

Bialystok, E., Craik, F., Luk, G., 2008. Cognitive control and lexical access in younger and older bilinguals. Journal of Experimental Psychology: Learning, Memory, & Cognition 34, 859–873. https://doi.org/10.1037/0278-7393.34.4.859.

Bigler, E.D., 2013. Traumatic brain injury, neuroimaging, and neurodegeneration. Frontiers in human neuroscience 7, 395. https://doi.org/10.3389/fnhum.2013.00395.

Bonato, M., Priftis, K., Marenzi, R., Zorzi, M., 2009. Normal and impaired reflexive orienting of attention after central nonpredictive cues. J. Cognit. Neurosci. 21, 745–759. https://doi.org/10.1162/jocn.2009.21054.

Brysbaert, M., Stevens, M., 2018. Power analysis and effect size in mixed effects models: a tutorial. Journal of Cognition 1 (1), 1–20. https://doi.org/10.5334/joc.10, 9.

Burnham, K.P., Anderson, D.R., 2002. Model Selection and Multimodel Inference: a Practical Information-Theoretic Approach, second ed. Springer-Verlag, New York.

Callejas, A., Shulman, G.L., Corbetta, M., 2014. Dorsal and ventral attention systems underlie social and symbolic cueing. J. Cognit. Neurosci. 26, 63–80. https://doi.org/10.1162/jocn_a_00461.

Cañadas, E., Lupiáñez, J., 2012. Spatial interference between gaze direction and gaze location: a study on the eye contact effect. Q. J. Exp. Psychol. 65 (8), 1586–1598. https://doi.org/10.1080/17470218.2012.659190.

Capozzi, F., Ristic, J., 2018. How attention gates social interactions. Ann. N. Y. Acad. Sci. 1426, 179–198. https://doi.org/10.1111/nyas.13854.

Chacón-Candia, J.A., Román-Caballero, R., Aranda-Martín, B., Casagrande, M., Lupiáñez, J., Marotta, A., 2022. Are there quantitative differences between eye-gaze and arrow cues? A meta-analytic answer to the debate and a call for qualitative differences. Neurosci. Biobehav. Rev. 144, 104993 https://doi.org/10.1016/j.neubiorev.2022.104993.

Colcombe, S.J., Kramer, A.F., Erickson, K.I., Scalf, P., 2005. The implications of cortical recruitment and brain morphology for individual differences in inhibitory function in aging humans. Psychol. Aging 20, 363–375. https://doi.org/10.1037/0882-7974.20.3.363.

Cremona-Meteyard, S.L., Clark, C.R., Wright, M.J., Geffen, G.M., 1992. Covert orientation of visual attention after closed head injury. Neuropsychologia 30, 123–132. https://doi.org/10.1016/0028-3932(92)90022-e.

Cremona-Meteyard, S.L., Geffen, G.M., 1994. Persistent visuospatial attention deficits following mild head injury in Australian Rules football players. Neuropsychologia 32, 649–662. https://doi.org/10.1016/0028-3932(94)90026-4.

Dahm, J., Wong, D., Ponsford, J., 2013. Validity of the Depression Anxiety Stress Scales in assessing depression and anxiety following traumatic brain injury. J. Affect. Disord. 151, 392–396. https://doi.org/10.1016/j.jad.2013.06.011.

Dalmaso, M., 2022. Exploring the social environment with the eyes: a review of the impact of facial stimuli on saccadic trajectories. Int. J. Environ. Res. Publ. Health 19 (24), 16615. https://doi.org/10.3390/ijerph192416615.

Dalmaso, M., Alessi, G., Castelli, L., Galfano, G., 2020a. Eye contact boosts the reflexive component of overt gaze following. Sci. Rep. 10, 4777. https://doi.org/10.1038/s41598-020-61619-6.

Dalmaso, M., Castelli, L., Galfano, G., 2020b. Social modulators of gaze-mediated orienting of attention: a review. Psychonomic Bulletin & Review 27, 833–855. https://doi.org/10.3758/s13423-020-01730-x.

Dalmaso, M., Castelli, L., Galfano, G., 2020c. Early saccade planning cannot override oculomotor interference elicited by gaze and arrow distractors. Psychonomic Bulletin & Review 27, 990–997. https://doi.org/10.3758/s13423-020-01768-x.

Dalmaso, M., Castelli, L., Priftis, K., Buccheri, M., Primon, D., Tronco, S., Galfano, G., 2015. Space-based and object-centered gaze cuing of attention in right hemisphere-damaged patients. Front. Psychol. 6, 1119. https://doi.org/10.3389/fpsyg.2015.01119.

Dalmaso, M., Galfano, G., Tarqui, L., Forti, B., Castelli, L., 2013. Is social attention impaired in schizophrenia? Gaze, but not pointing gestures, is associated with spatial attention deficits. Neuropsychology 27 (5), 608. https://doi.org/10.1037/a0033518.

Dalmaso, M., Petri, L., Patron, E., Spoto, A., Vicovaro, M., 2022. Direct gaze holds attention, but not in individuals with obsessive-compulsive disorder. Brain Sci. 12, 288. https://doi.org/10.3390/brainsci12020288.

Driver, J., Davis, G., Ricciardelli, P., Kidd, P., Maxwell, E., Baron-Cohen, S., 1999. Gaze perception triggers reflexive visuospatial orienting. Vis. Cognit. 6, 509–540. https://doi.org/10.1080/135062899394920.

Ekman, P., 1992. An argument for basic emotions. Cognit. Emot. 6, 169–200. https://doi.org/10.1080/02699939208411068.

Emery, N.J., 2000. The eyes have it: the neuroethology, function and evolution of social gaze. Neurosci. Biobehav. Rev. 24, 581–604. https://doi.org/10.1016/S0149-7634(00)00025-7.

Ferrell, R.B., Tanev, K.S., 2002. Traumatic brain injury in older adults. Curr. Psychiatr. Rep. 4 (5), 354–362. https://doi.org/10.1007/s11920-002-0083-9.

Friesen, C.K., Kingstone, A., 1998. The eyes have it! Reflexive orienting is triggered by nonpredictive gaze. Psychonomic Bulletin & Review 5, 490–495. https://doi.org/10.3758/BF03208827.

Frischen, A., Bayliss, A.P., Tipper, S.P., 2007. Gaze cueing of attention: visual attention, social cognition, and individual differences. Psychol. Bull. 133, 694–724. https://doi.org/10.1037/0033-2909.133.4.694.

Frost, R.B., Farrer, T.J., Primosch, M., Hedges, D.W., 2013. Prevalence of traumatic brain injury in the general adult population: a meta-analysis. Neuroepidemiology 40, 154–159. https://doi.org/10.1159/000343275.

Galfano, G., Dalmaso, M., Marzoli, D., Pavan, G., Coricelli, C., Castelli, L., 2012. Eye gaze cannot be ignored (but neither can arrows). Q. J. Exp. Psychol. 65, 1895–1910. https://doi.org/10.1080/17470218.2012.663765.

Georgiou, G., Bleakley, C., Hayward, J., Russo, R., Dutton, K., Eltiti, S., Fox, E., 2005. Focusing on fear: attentional disengagement from emotional faces. Vis. Cognit. 12, 145–158.

Hietanen, J.K., 2018. Affective eye contact: an integrative review. Front. Psychol. 9, 1587. https://doi.org/10.3389/fpsyg.2018.01587.

Hietanen, J.K., Myllyneva, A., Helminen, T.M., Lyyra, P., 2016. The effects of genuine eye contact on visuospatial and selective attention. J. Exp. Psychol. Gen. 145, 1102–1106.

Hommel, B., Pratt, J., Colzato, L., Godijn, R., 2001. Symbolic control of visual attention. Psychol. Sci. 12, 360–365. https://doi.org/10.3758/APP.71.2.363.

Kuhn, G., Benson, V., Fletcher-Watson, S., Kovshoff, H., McCormick, C.A., Kirkby, J., Leekam, S.R., 2010. Eye movements affirm: automatic overt gaze and arrow cueing for typical adults and adults with autism spectrum disorder. Exp. Brain Res. 201, 155–165. https://doi.org/10.1007/s00221-009-2019-7.

Kim, Y.H., Yoo, W.K., Ko, M.H., Park, C.H., Kim, S.T., Na, D.L., 2009. Plasticity of the attentional network after brain injury and cognitive rehabilitation. Neurorehabilitation Neural Repair 23, 468–477. https://doi.org/10.1177/1545968308328728.

Kristjánsson, A., 2011. The intriguing interactive relationship between visual attention and saccadic eye movements. In: Liversedge, S.P., Gilchrist, I.D., Everling, S. (Eds.), The Oxford Handbook of Eye Movements. Oxford University Press, Oxford, England, pp. 455–470.

Langner, O., Dotsch, R., Bijlstra, G., Wigboldus, D.H., Hawk, S.T., Van Knippenberg, A.D., 2010. Presentation and validation of the Radboud faces database. Cognit. Emot. 24, 1377–1388. https://doi.org/10.1080/02699930903485076.

Lenth, R.V., 2016. Least-squares means: the R package lsmeans. J. Stat. Software 69, 1–33. https://doi.org/10.18637/jss.v069.i01.

Lin, X., Zhang, X., Liu, Q., Zhao, P., Zhang, H., Wang, H., Yi, Z., 2021. Theory of mind in adults with traumatic brain injury: a meta-analysis. Neuroscience and Biobehavioural Review 121, 106–118. https://doi.org/10.1016/j.neubiorev.2020.12.010.

Marotta, A., Lupianez, J., Martella, D., Casagrande, M., 2012. Eye gaze versus arrows as spatial cues: two qualitatively different modes of attentional selection. J. Exp. Psychol. Hum. Percept. Perform. 38, 326–335.

Marotta, A., Pasini, A., Menotti, E., Pasquini, A., Pitzianti, M.B., Casagrande, M., 2017. Controlling attention to gaze and arrows in attention deficit hyperactivity disorder. Psychiatr. Res. 251, 148–154. https://doi.org/10.1016/j.psychres.2017.01.094.

Mathias, J.L., Wheaton, P., 2007. Changes in attention and information-processing speed following severe traumatic brain injury: a meta-analytic review. Neuropsychology 21, 212–223.

McDonald, S., 2013. Impairments in social cognition following severe traumatic brain injury. J. Int. Neuropsychol. Soc. 19, 231–246. https://doi.org/10.1017/S1355617712001506.

McKay, K.T., Grainger, S.A., Coundouris, S.P., Skorich, D.P., Phillips, L.H., Henry, J.D., 2021. Visual attentional orienting by eye gaze: a meta-analytic review of the gaze-cueing effect. Psychol. Bull. 147, 1269–1289. https://doi.org/10.1037/bul0000353.

Milders, M., 2019. Relationship between social cognition and social behaviour following traumatic brain injury. Brain Inj. 33, 62–68. https://doi.org/10.1080/02699052.2018.1531301.

Muller, F., Simion, A., Reviriego, E., Galera, C., Mazaux, J.M., Barat, M., Joseph, P.A., 2010. Exploring theory of mind after severe traumatic brain injury. Cortex 46, 1088–1099. https://doi.org/10.1016/j.cortex.2009.08.014.

Murphy, J.M., Bennett, J.M., de la Piedad Garcia, X., Willis, M.L., 2022. Emotion recognition and traumatic brain injury: a systematic review and meta-analysis. Neuropsychological Review 32, 520–536. https://doi.org/10.1007/s11065-021-09510-7.

Narison, R., de Montalembert, M., Bayliss, A., Conty, L., 2021. Measuring gaze and arrow cuing effects with a short test adapted to brain damaged patients with unilateral spatial neglect: a preliminary study. Front. Psychol. 12, 1–9. https://doi.org/10.3389/fpsyg.2021.690197.

Narison, R., de Montalembert, M., Conty, L., 2020. Diagnosing gaze and arrow cueing effects in unilateral spatial neglect. Neurocase 26, 42–50. https://doi.org/10.1080/13554794.2019.1705495.

Olver, J.H., Ponsford, J.L., Curran, C., 1996. Outcome following traumatic brain injury: a comparison between 2 and 5 years after injury. Brain Inj. 10, 841–848.

Peeters, W., van den Brande, R., Polinder, S., Brazinova, A., Steyerberg, E.W., Lingsma, H.F., Maas, A.I., 2015. Epidemiology of traumatic brain injury in Europe. Acta Neurochirgica 157, 1683–1696. https://doi.org/10.1007/s00701-015-2512-7.

Posner, M.I., 1980. Orienting of attention. Q. J. Exp. Psychol. 32, 3–25. https://doi.org/10.1080/00335558008248231.

Quadflieg, S., Mason, M.F., Macrae, C.N., 2004. The owl and the pussycat: gaze cues and visuospatial orienting. Psychonomic Bulletin & Review 11, 826–831. https://doi.org/10.3758/bf03196708.

Reid, V.M., Dunn, K., Young, R.J., Amu, J., Donovan, T., Reissland, N., 2017. The human fetus preferentially engages with face-like visual stimuli. Curr. Biol. 27, 1825–1828. https://doi.org/10.1016/j.cub.2017.05.044.

Robertson, K., Schmitter-Edgecombe, M., 2017. Focused and divided attention abilities in the acute phase of recovery from moderate to severe traumatic brain injury. Brain Inj. 31, 1069–1076. https://doi.org/10.1080/02699052.2017.1296192.

Román-Caballero, R., Marotta, A., Lupiáñez, J., 2021. Target-background segregation in a spatial interference paradigm reveals shared and specific attentional mechanisms triggered by gaze and arrows. J. Exp. Psychol. Hum. Percept. Perform. 47, 1561. https://doi.org/10.1037/xhp0000953.

Schmitter-Edgecombe, M., Kibby, M.K., 1998. Visual selective attention after severe closed head injury. J. Int. Neuropsychol. Soc. 4, 144–159. https://doi.org/10.1017/s1355617798001441.

Senju, A., Tojo, Y., Dairoku, H., Hasegawa, T., 2004. Reflexive orienting in response to eye gaze and an arrow in children with and without autism. JCPP (J. Child Psychol. Psychiatry) 45 (3), 445–458. https://doi.org/10.1111/j.1469-7610.2004.00236.x.

Sharp, D.J., Scott, G., Leech, R., 2014. Network dysfunction after traumatic brain injury. Nat. Rev. Neurol. 10, 156–166. https://doi.org/10.1038/nrneurol.2014.15.

Shepherd, S.V., 2010. Following gaze: gaze-following behavior as a window into social cognition. Front. Integr. Neurosci. 4, 5. https://doi.org/10.3389/fnint.2010.00005.

Stephenson, L.J., Edwards, S.G., Bayliss, A.P., 2021. From gaze perception to social cognition: the shared-attention system. Perspect. Psychol. Sci. 16, 553–576. https://doi.org/10.1177/1745691620953773.

Symonds, C.P., Ritchie Russell, W., 1943. Accidental head injuries: prognosis in service patients. Lancet 241, 7–10. https://doi.org/10.1016/S0140-6736(00)70687-8.

Teasdale, G., Jennett, B., 1974. Assessment of coma and impaired consciousness. A practical scale. Lancet 2, 81–84. https://doi.org/10.1016/s0140-6736(74)91639-0.

Tipples, J., 2002. Eye gaze is not unique: automatic orienting in response to uninformative arrows. Psychonomic Bulletin & Review 9, 314–318. https://doi.org/10.3758/BF0319628.

Ubukata, S., Tanemura, R., Yoshizumi, M., Sugihara, G., Murai, T., Ueda, K., 2014. Social cognition and its relationship to functional outcomes in patients with sustained acquired brain injury. Neuropsychiatric Dis. Treat. 10, 2061–2068. https://doi.org/10.2147/NDT.S68156.

Van Zomeren, A.H., Van den Burg, W., 1985. Residual complaints of patients two years after severe head injury. Journal of Neurology, Neurosurgery, and Psychiatry 48, 21–28. https://doi.org/10.1136/jnnp.48.1.21.

Vecera, S.P., Rizzo, M., 2004. What are you looking at? Impaired 'social attention' following frontal-lobe damage. Neuropsychologia 42, 1657–1665. https://doi.org/10.1016/j.neuropsychologia.2004.04.009.

Vecera, S.P., Rizzo, M., 2006. Eye gaze does not produce reflexive shifts of attention: evidence from frontal-lobe damage. Neuropsychologia 44, 150–159. https://doi.org/10.1016/j.neuropsychologia.2005.04.010.

Vuilleumier, P., 2002. Perceived gaze direction in faces and spatial attention: a study in patients with parietal damage and unilateral neglect. Neuropsychologia 40, 1013–1026. https://doi.org/10.1016/S0028-3932(01)00153-1.

Walz, J.A., Mani, R., Alnawmasi, M.M., Khuu, S.K., 2021. Visuospatial attention allocation as an indicator of cognitive deficit in traumatic brain injury: a systematic review and meta-analysis. Front. Hum. Neurosci. 20, 675376 https://doi.org/10.3389/fnhum.2021.675376.

Whelan-Goodinson, R., Ponsford, J., Johnston, L., Grant, F., 2009. Psychiatric disorders following traumatic brain injury: their nature and frequency. J. Head Trauma Rehabil. 24, 324–332. https://doi.org/10.1097/HTR.0b013e3181a712aa.

Zeiträg, C., Jensen, T.R., Osvath, M., 2022. Gaze following: a socio-cognitive skill rooted in deep time. Front. Psychol. 13, 950935 https://doi.org/10.3389/fpsyg.2022.950935.

Zhang, H., Zhang, X.N., Zhang, H.L., Huang, L., Chi, Q.Q., Zhang, X., Yun, X.P., 2016. Differences in cognitive profiles between traumatic brain injury and stroke: a comparison of the Montreal Cognitive Assessment and Mini-Mental State Examination. Chin. J. Traumatol. 19, 271–274. https://doi.org/10.1016/j.cjtee.2015.03.007.

Zigmond, A.S., Snaith, R.P., 1983. The hospital anxiety and depression scale. Acta Psychiatr. Scand. 67, 361–370. https://doi.org/10.1111/j.1600-0447.1983.tb09716.x.