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Emotion recognition and eye tracking of static and dynamic facial affect: Acomparison of individuals with and without traumatic brain injury

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ABSTRACT

Diminished social functioning is often seen after traumatic brain injury (TBI). Mechanisms contributing to these deficits are poorly understood but thought to relate to impaired ability to recognize facial expressions. Static stimuli are often used to investigate ability post-TBI, and there is less evidence using more *real-life* dynamic stimuli. In addition, most studies rely on behavioral responses alone. The present study investigated the performance of a TBI group and matched non-TBI group on static and dynamic tasks using eye-tracking technology alongside behavioral measures. This is the first study to use eye tracking methodology alongside behavioral measures in emotion recognition tasks in people with brain injury. Eighteen individuals with heterogeneous TBI and 18 matched non-TBI participants were recruited. Stimuli representing six core emotions (Anger, Disgust, Fear, Happy, Sad, and Surprise faces) were selected from the Amsterdam Dynamic Facial Expression Set (ADFES). Participants were instructed to identify the emotion displayed correctly whilst eye movement metrics were recorded.

Results: Results of analyses showed that TBI patients had First Fixation to nose for all emotion stimuli, shorter Fixation Duration and lower Fixation Count to eyes, were generally slower to classify stimuli, and less accurate than non-TBI group for the static task. Those with TBI were also less accurate at identifying Angry, Disgust, and Fear stimulus faces compared to the non-TBI group during the dynamic unfolding of an emotion.

Conclusion: In the present study, those with TBI had atypical eye scan patterns during emotion identification in the static emotion recognition task compared to the non-TBI group and were associated with lower identification accuracy on behavioral measures in both static and dynamic tasks. Findings suggest potential disruption to oculomotor systems vital for first stage perceptual processing. Arguably, these impairments may contribute to diminished social functioning.

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Introduction

It is estimated that approximately 10 million traumatic brain injuries (TBI) occur worldwide each year representing a global health problem (Dewan et al., 2018). TBI results in a cluster of deficits cross-cutting cognitive and socioemotional domains (Kelly et al., 2017). Importantly, socioemotional deficits produce worse outcomes compared to other deficits, adversely affecting quality of life, relationships, employment prospects, independence, and autonomy post-injury (Ponsford et al., 2014).

It is not yet known whether diminished ability to recognize emotion in others after brain injury results from disruption to early visual processing pathways (producing abnormal eye scan patterns) or upon higher socio-cognitive functions, or both. Importantly, impaired emotion identification risks compromised social relationships, social isolation, and even possible physical and mental harm (Jack & Schyns, 2015). These negative consequences compound post-injury socioemotional and cognitive impairments, further impeding rehabilitative efforts, diminishing quality of life, employment prospects, and even life expectancy (Brooks et al., 2015).

Typically, swift accurate identification of others' emotional expressions is central to adaptive social functioning (Jack & Schyns, 2015). Jack and Schyns (2015) proposed that social interaction depends upon dynamic exchange of patterns of information conveyed through facial expression to achieve mutual understanding. From this perspective, interpretation of facial expressions provides the cornerstone of social interaction and complex socio-cognitive processes.

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Biszak and Babbage (2014) hypothesized that communication and relationship problems post-TBI are at least partially attributable to impaired emotion recognition and that between 13% and 39% of those with moderate-to-severe TBI have problems recognizing emotional expressions. At the global level, this estimate equates to between 1,300,000 and 3,900,000 individuals worldwide experiencing intractable and poorly understood social impairments post-TBI. Additionally, socioemotional impairments are often overlooked by health professionals (Kelly et al., 2017), and therapeutic intervention may be absent or piecemeal, lacking a cohesive underlying conceptual framework (Ubukata et al., 2014).

Murphy et al. (2021) conducted a meta-analysis of the emotion recognition literature in those with TBI to estimate the magnitude of the problem. Briefly, the results of this systematic review indicated significant emotion recognition impairment in those with TBI, and the impact of severity of injury was indeterminate, although this likely reflected limitations in reporting of injuries in the included studies. Murphy et al. (2021) made recommendations about the growing use of dynamic stimuli in studies and the need for more data in this area. Importantly, the precise neural correlates of impaired emotion recognition remain to be determined, and it is not known whether the deficit lies in early visual processing or is caused by impaired integration of visual and socioemotional information higher upstream. Understanding these mechanisms has been hampered by experimental bias to behavioral responses to emotion stimuli, and few studies have tracked eyes capturing *real time* physiological data in those with a brain injury.

Knox and Douglas (2009) investigated facial emotion recognition using static and dynamic stimuli in TBI and non-TBI groups. They found that the TBI group was generally impaired on behavioral measures compared to the non-TBI group, regardless of stimulus type. These impairments are not restricted to those with severe brain injuries but are also seen in mild and moderate brain injuries (Kubu, 1999).

Appropriate visual face scanning refers to the capacity to direct eye gaze (synchronously) and instantiates adequate fixation duration to the most information-laden component of the visual scene when communicating with others in social contexts. It is taken as axiomatic that these mechanisms are automatic, hard-wired, and robust to injury. The integration of eye scan patterns, saccades, fixation duration, focussed attention, salience identification (Schurgin et al., 2014) and socioemotional knowledge makes demands upon multiple neural systems working synergistically (Gobel et al., 2015). One or more of these mechanisms can be affected by brain trauma (Matsumoto et al., 2015) so impairments can be seen at any level of the processing pathway. Hence, the notion that the visual system is *hard-wired* to detect biological motion is potentially misleading when evaluating functional consequences of brain trauma (Yovel & O'Toole, 2016). Supposedly, *hard-wired* functions depend upon the integrity of organic neural systems as with all brain functions.

Research findings have shown that eye scan patterns can be disrupted by disease or trauma adversely affecting emotion perception and social functioning. Atypical eye scan patterns and impaired emotion recognition have been observed in Huntington's disease, autism spectrum disorder, and schizophrenia (Grynszpan & Nadel, 2015; Kordsachia et al., 2018; Tsang, 2018). Less is known about the potential effect of traumatic brain injuries on typical eye scan patterns. However, Danna-Dos-Santos et al. (2018) found that mild TBI resulted in abnormal saccadic eye movements in response to environmental stimuli, suggesting that these mechanisms are susceptible to injury. Thus, there is some limited evidence that impaired eye scan patterns (and consequently emotion recognition) might co-occur post-TBI (Douglas et al., 2010; Kenrick et al., 2017).

Anatomically, several frontal brain regions (together with subcortical nuclei) are associated with eye movements including frontal eye fields, supplementary eye fields, and dorsolateral prefrontal cortex networks (Sparks, 2002). Frontotemporal areas are particularly susceptible to injury due to their position in the skull and the trajectory of the brain on impact (Barker et al., 2010). Accordingly, frontotemporal brain regions, that include these early visual processing pathways, are areas most likely to be injured during head trauma (Barker et al., 2010, 2018).

Research in the area has traditionally focussed on emotion recognition using static faces with purely behavioral responses as dependent variables without measures of eye tracking patterns. Whilst these findings are informative, in the real-world faces are in constant motion during communication, and include eye movements, blinking, facial muscle changes, mouth movements, mannerisms, nodding and movement of head. All these movements must be *tracked* by the perceiver, in real time, to correctly identify and interpret these non-verbal cues. Hence, it is useful to conduct research in this area using ecologically valid stimuli and objective physiological measures in both static and dynamic tests. In the present study, we combined behavioral measures alongside physiological eye tracking measures in static and dynamic emotion recognition tasks to establish whether eye tracking metrics corresponded to

behavioral responses. This approach provides a start point for understanding the neural mechanisms potentially contributing to well-observed behavioral deficits in stimulus processing for static and dynamic emotions post-injury.

Hypotheses

1. The TBI group will be less accurate at recognizing emotion than the non-TBI group for static and dynamic tasks.
2. The TBI and non-TBI group will elicit different eye scan patterns on static and dynamic tasks.

Materials and method

The study included 18 TBI participants and 18 matched non-TBI participants (N = 36, for static and N = 34 for dynamic task). Due to a corrupted dataset, there were two fewer participants (one person with TBI plus their matched non-TBI participant) for the dynamic task. The study protocol was approved by Leeds East NHS Research Ethics Committee and Sheffield Hallam University Faculty Research Ethics. TBI participants were recruited through two Brain Injury Services within the UK National Health Service. The non-TBI group was recruited by stratified opportunity and snowballing sampling and matched for gender, age, and education to the TBI participants. TBI and non-TBI groups completed screening measures to establish whether they had any visual defects or incidence of severe depression or anxiety (see below). All participants gave informed consent and completed both the static and dynamic tasks whilst undergoing eye tracking.

Inclusion/exclusion criteria

TBI inclusion criteria

Traumatic brain injury sustained in adulthood is established by assessment at hospital admission or brain pathology based on imaging scans. Participants were at least one-year post injury to ensure that chronic rather than acute effects of brain injury were measured. They were aged between 18 and 65 to account for any effects of natural aging. Average time since injury was 8.5 years (see Table 1).

Exclusion criteria for all participants

History of psychiatric illness or severe recent drug and alcohol abuse was assessed by Michigan Alcohol Screening Test (MAST; Selzer, 1971) and Drug Abuse Screening Test (DAST; Skinner, 1982). All participants were screened for depression and anxiety using the Hospital Anxiety and Depression Scale (HADS; Zigmond & Snaith, 1983) and for visual deficits using the Visual Object and Space Perception Battery (VOSPB; Warrington & James, 1991), and Cortical Vision Screening Test (CORVIST; Warrington et al., 2001). None of the participants had visual defects measured by screening tasks and none met the criteria for severe anxiety or depression. However, the TBI group did have higher overall anxiety score based on the HADS measure (anxiety M = 8.11, SD = 4.61, depression M = 6.00, SD = 3.31, overall HAD's M = 14.11, SD = 6.28); matched non-TBI group (Anxiety M = 4.94, SD = 2.04, depression M = 2.67, SD = 1.94, overall HAD's M = 7.61, SD = 3.48). Anxiety levels were mildly raised, but this pattern is not unusual in post-TBI populations (Kreutzer et al., 2001).

Information regarding TBI was obtained from medical records, including scan data and hospital admission notes. Participant injuries were heterogeneous, including brain hemorrhage, skull fracture, and contusion, which is typical for this patient cohort. Mechanisms of injury included assault, road traffic accidents, falls, and pedestrian collisions. Thirteen participants had frontal lobe pathology, five had pathology outside of frontal cortices to other cortical and/or subcortical regions (see Appendix A).

Table 1. Mean, standard deviations (*SD*), significance (*p*), and effect size (Cohen's *d*) for demographic variables for TBI and non-TBI groups: dynamic (N = 36) and static (N = 34) experiments.

Demographic Variable	TBI group mean (*SD*)	Non-TBI Group mean (*SD*)	*p*	*d*
Gender	*m* = 15, *f* = 2	*m* = 15, *f* = 2		
Static Task	*m* = 15, *f* = 3	*m* = 15, *f* = 3		
Dynamic Task				
Age at Test	43.00 *(12.10)*	44.18 *(11.58)*	.708	0.10
Static Task	44.94 *(11.69)*	43.83 *(12.26)*	.696	0.09
Dynamic Task				
Age at Injury (yrs)	36.71 *(14.17)*			
Static Task	36.44 *(13.79)*			
Dynamic Task				
Post Injury Years	7.47 *(7.73)*			
Static Task	8.50 *(8.68)*			
Dynamic Task				
Years of Education	14.82 *(4.38)*	15.47 *(3.74)*	.454	0.16
Static Task	14.83 *(4.25)*	15.56 *(3.65)*	.389	0.18
Dynamic Task				
Verbal IQ	83.13 *(19.08)*	95.06 *(8.85)*	.013	0.85
Static Task	84.06 *(18.71)*	95.33 *(8.66)*	.007	0.82
Dynamic Task				
Performance IQ	92.93 *(14.73)*	104.29 *(11.85)*	.027	0.85
Static Task	91.00 *(17.50)*	104.72 *(11.64)*	.015	0.94
Dynamic Task				
Full Scale IQ	84.73 *(17.73)*	99.65 *(10.61)*	.008	1.05
Static Task	90.25 *(19.69)*	100.06 *(10.44)*	.025	0.65
Dynamic Task				

Injury severity

There are two cardinal measures of assessment of TBI severity, duration of Post-Traumatic Amnesia (PTA), and loss of consciousness based on Glasgow Coma Scale (GCS – Teasdale & Jennett, 1974). PTA score is calculated from injury onset until the patient has reliable and continuous memory for daily events (McMillan, 2015), PTA less than 24 hours = Mild TBI, greater than 24 hours but 7 days or less = Moderate PTA, greater than 7 days = Severe. TBI Participants were classified as follows in terms of injury severity – 16 severe, one moderate, and one mild TBI. Referring clinicians established severity of injury rating based on standard procedures – Glasgow Coma Scale (Teasdale & Jennett, 1974; GCS), loss of consciousness scores and post-traumatic amnesia (PTA) length (Marshman et al., 2013). The GCS assesses motor, verbal, and eye responses providing a score between 3 and 15. Scores between 3 and 8 = Severe, between 9 and 12 = Moderate, and those between 13 and 15 = Mild (Teasdale & Jennett, 1974). We recruited more males than females, an anticipated effect in line with existing evidence that males are up to three times more likely to sustain a brain injury compared to females. See Table 1 for demographic and clinical characteristics of TBI participants and non-TBI groups.

Groups were not different in years of education, but those with TBI fell significantly below the non-TBI group for Verbal, Performance, and Full-Scale IQ scores. This is a pattern often seen after brain injury and indicates a significant brain injury in those with TBI (Barker et al., 2010, 2018). The non-TBI group were neurotypical with no history of brain injury or concussion.

Design

A quasi-experimental design was used to compare the TBI and non-TBI groups on recognition ability for six core emotional stimuli (Anger, Disgust, Fear, Happy, Sad, and Surprise) from static and dynamic facial expressions presented on screen. Tobii T120 Eye Tracker (Tobii Technologies, Stockholm, Sweden) captured eye scan variables including Time to First Fixation, First Fixation Duration, Total Fixation Duration, and Total Fixation Count to three areas of interest (AOI) including eyes, nose, and mouth.

Stimuli and procedure

Thirty-six pictures and 36 video clips were selected from the Amsterdam Dynamic Facial Expression Set (ADFES; Van der Schalk et al., 2011) for static and dynamic experiments, respectively. The ADFES was selected as the data set includes both static and dynamic emotion recognition stimuli that did not differ on any dimension other than presentation mode, thus controlling for potential confounding variables on results (background color, models enacting the emotion, lighting etc.,). Van der Schalk et al. (2011) established that the ADFES has good recognition scores. Additionally, this measure is gaining some traction in emotion research (Wingenbach et al., 2016; Żurowska et al., 2018). Six core emotional stimuli (Happy, Sad, Anger, Surprise, Fear, and Disgust) were selected corresponding to Ekman's (1992) identification of the six basic emotions. The primary behavioral score for static and dynamic experiments was emotion identification accuracy (the number of correct expression-emotion matches). Only correct responses were included in all analyses. There was one practice trial at the beginning of each static and dynamic experiment. Each of the six basic emotions was presented six times, three times by a female actor and three times by a male actor equaling 36 images in the static task and 36 in the dynamic task. Stimulus order was randomized.

In a typical experimental setup, static stimuli have self-determined exposure durations to a fixed apex expression. This is to exclude speed of responding as a confound to accuracy, whereby on a task with pre-set duration results might reflect speed of responding rather than emotion recognition accuracy. This is a particularly important consideration for those who have sustained TBI and can be impulsive or conversely have slowed processing speed. The two tasks were designed to be used together for a comprehensive evaluation of emotion recognition. Most studies to date have used static tasks, but without eye tracking – so our study brings another dimension to evaluation of emotion recognition using static stimuli post-TBI with eye tracking, and the same test dynamic stimuli version and eye tracking. In this way, we could establish whether any purported deficits in the TBI group were associated with emotion recognition in a static or moving scenario and whether eye scan patterns revealed any additional information about mechanisms contributing to emotion judgments.

Static experiment

ADFES photographs consisted of video clips frozen at the apex of an unfolding emotion. The photograph remained on screen for 8 seconds or until the participant made the key press selection and the nature of the response (correct or incorrect) and RT was recorded.

The eight-second stimulus onset latency was chosen based on pilot data with an emotionally neutral task and the eye tracking apparatus. None of the participants exceeded the 8 second cutoff in their response and these data helped determine exposure time for dynamic stimuli. Eye tracking data were collected for the entire stimulus exposure time. Instructions stated that response time was recorded but participants were encouraged to focus on accuracy rather than speed. The purpose of this explicit instruction was to prevent impulsive responding by the group with severe TBI.

Dynamic experiment

For the dynamic task, participants watched each video clip activated by the experimenter, then provided their judgment on the emotion presented and clicked the spacebar to move on to the next trial. Reaction time data was not collected during the dynamic task. Video clip timings followed the standard protocol for the ADFES. At the start of the clip, the model presented with a neutral face for 0.5 seconds followed by the unfolding emotion for 5.5 seconds (6 seconds in total). Eye tracking data were collected for the entire stimulus exposure time. Graphical depiction of the experimental procedures is presented in Appendix B

Task design

On the static task, responses were timed, and we set the maximum exposure time to 8 seconds to account for potential slow responses of those with TBI – we also provided instructions to guard against impulsive responses in those with TBI. The mean response time was 2785.24 milliseconds = 0.5 minutes overall for the non-TBI group, and the mean response time was 4743.61 milliseconds = 0.8 minutes for the TBI group. These data assured us that the TBI patients could complete the dynamic task after exposure to the stimuli for 6 seconds. In the dynamic task, participants verbally stated their response, and this was not timed as the clip lasted 6 seconds and then a response was required. Thus, the two tasks were different in this respect. They were also similar in that the models used in both tasks were the same, and color, background, and luminance of the stimuli were the same.

Apparatus

We recorded eye scanning activity using a Tobii T120 eye-tracker and Tobii Studio Eye Tracking Analysis software (Tobii Technologies, Stockholm, Sweden). The eye-tracker has a 17-inch thin-film-transistor screen (1280x1024 pixels) with an embedded infrared camera without an obtrusive head frame allowing freedom for natural head and eye movement. Eye tracking data was sampled at 120 Hz with an accuracy of 0.5°. The default Tobii fixation filter algorithm was utilized during both experiments, setting the fixation threshold at 35 pixels for velocity and 35 pixels for distance per sample. If the velocity of the eye movement was above the 0.5° per second threshold, then the eye movement was classified as a saccade sample and below it was classed as a fixation. The eye tracker was calibrated for each participant prior to each experiment using standard five-point calibration of each eye. Participants were seated approximately 50 cm away from the screen in a stationary chair.

Eye tracking metrics

A brief description of how each eye tracking metric was computed is provided below. Metrics were calculated by the eye tracking software.

Time to first fixation (Seconds)

Time to first fixation is a measurement of the latency from stimulus start until the participant fixates on an active AOI (area of interest) within a static picture or dynamic video clip. Measurement stops when the participant fixates on an active AOI. Media not containing the AOI is excluded from the recording time calculation.

First fixation duration (Seconds)

This calculation measures the first fixation latency on an active AOI. If the participant does not fixate on an AOI by the end of the recording, then the first fixation value is not provided and is not incorporated in the descriptive statistics calculations.

Total fixation duration (Seconds)

This calculation is the sum of the duration for all fixations within an active AOI. The N value is therefore based on the number of recordings.

Fixation count (Count)

This metric calculates the number of times the participant fixates on an active AOI. If the participant stops fixating on an AOI and moves their attention to another area of the media but later fixates again on the AOI, then all fixation counts are amalgamated

at the end of the media. If the participant does not fixate on an AOI by the end of the recording, then the fixation count value is not provided and will not be incorporated in the descriptive statistics calculations.

Results

Raw data were checked for parametric assumptions, some data violated normality for behavioral and eye tracking data. This is not unusual in neuropsychological studies where participants are not expected to perform *typically*. Analyses were conducted on untransformed data to avoid limitations associated with transforming data and to gauge against correcting for accurate but non-normal data (Feng et al., 2014). Given the relatively small sample size the α for all analyses was set at .05. The analyses were also repeated using appropriate non-parametric statistical tests and these showed similar results to the parametric analyses presented here(Figure 1).

Experiment one – static stimuli

Table 2 shows means and standard deviations for the number of correctly identified emotions for TBI and non-TBI groups. Those with TBI were least accurate at identifying the emotion Fear, and the same held for the non-TBI group. The TBI group was most accurate on the Happy stimulus face followed by Surprise stimuli, and non-TBI group was similarly accurate for Happy and Disgust, albeit performing at ceiling level unlike the TBI group.

Accuracy and latency data were analyzed with 2*(6) ANOVAs to explore possible group differences for emotion labeling accuracy and reaction time scores on the ADFES static task. Four 2*(6*3) mixed-design ANOVAs were also conducted for the four eye-tracking metrics (time to first fixation, first fixation duration, total fixation duration, and total fixation count) to areas of interest.

Emotion identification accuracy

Results of a 2 × (group) *6 (emotion) mixed-design ANOVA showed a main effect of group (F (1, 32) = 14.61, p = .001, ηp^2 = 0.31) and emotion (F (10.26, 110.15) = 10.26, p = .001, η_p^2 = 0.24) on emotion identification accuracy. There was also a significant interaction for emotion and group (F (3.44, 110.15) = 5.14, p = .001, η_p^2 = 0.14). Results of pairwise comparisons showed that the TBI group was less accurate than the non-TBI group at identifying Anger, Disgust, Fear, and Sad faces (see Table 2 for p-values).

Table 3 shows reaction time data in milliseconds to static stimulus faces for the TBI and non-TBI groups. Findings were in line with accuracy data, the TBI group were fastest to Happy and Surprise stimuli and showed greatest response latencies to the Fear stimuli. The non-TBI group was almost twice as fast as the TBI group, although neither group exceeded the 8 second cutoff. Results of the ANOVA showed a significant main effect of group (F (1, 32) = 4.86, p = .035, $\eta p2$ = 0.13) and

Table 2. Mean, standard deviations (*SD*), significance (*p),* and effect size (Cohen's *d*) for number of correctly identified emotions for the static task for TBI and non-TBI groups.

ADFES emotion stimulus	TBI group mean (*SD*)	Non-TBI group mean (*SD*)	*p*	*d*
Anger	4.00 (1.73)	5.65 (0.86)	.001	1.27
Disgust	4.24 (2.14)	6.00 (0.00)	.002	1.64
Fear	3.76 (2.05)	5.41 (0.71)	.004	1.20
Happy	5.94 (0.24)	6.00 (0.00)	.325	0.50
Sad	4.94 (1.25)	5.71 (0.59)	.029	0.84
Surprise	5.47 (1.23)	5.88 (0.33)	.192	0.53
Overall total score	28.35 (6.62)	34.65 (1.50)	.001	1.55

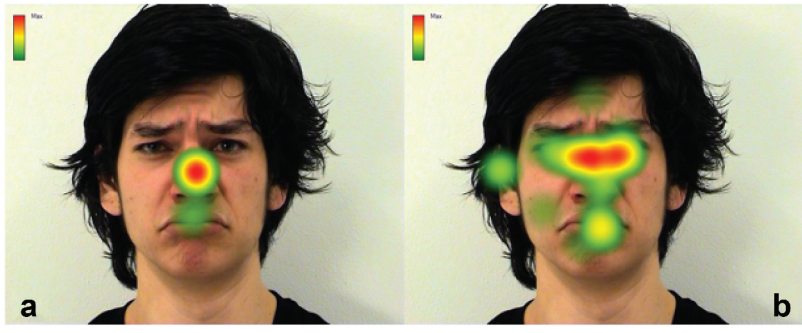

Figure 1. Legend: 1 A heat map showing eye scan patterns for a male TBI participant (a) and a matched non-TBI participant (b) when viewing a static sad facial expression. The heat map displays the number and length of fixations with red indicating maximum levels. Note the lack of attention to eyes and fixation on the nose in the TBI participant.

Table 3. Mean, standard deviations *(SD)*, significance (*p),* and effect size (Cohen's *d*) for reaction time for correct responses for the static task for TBI and non-TBI group (milliseconds).

ADFES emotion stimulus	TBI Group mean (*SD*)	Non-TBI Group mean (*SD*)	*p*	*d*
Anger	4500.35 (2673.73)	3265.03 (1704.20)	.118	0.56
Disgust	4720.33 (4338.31)	2372.87 (851.21)	.036	0.90
Fear	5350.31 (3322.14)	3198.37 (1772.11)	.025	0.84
Happy	2879.02 (1122.40)	2439.28 (973.57)	.231	0.42
Sad	5142.48 (4998.24)	2849.91 (1009.19)	.073	0.85
Surprise	3649.15 (2026.67)	2585.99 (928.38)	.058	0.72
Overall Mean	4743.61 (3080.25)	2785.24 (1206.44)	.107	0.91

emotion on reaction time (F (2.41, 77.25) = 5.14, p = 005, η_p^2 = 0.14); however, the interaction between emotion and group was not significant (F (2.41, 77.25) = 2.21, p = .107, η_p^2 = 0.07). For the main effect of emotion, post hoc pairwise comparisons showed faster response times to Happy compared to Angry (p = .001, d = 0.79), and Fear stimulus faces (p = .001 d = 1.00), and to Surprise compared to Fear stimulus faces (p = .001 d = 0.62). Interestingly, although the TBI group took significantly longer to respond than the non-TBI group, they were still *less* accurate in correctly identifying emotions, indicating that there was no speed-accuracy trade-off.

Table 4 presents means and standard deviations for TBI and non-TBI group on the eye tracking metrics in the static task; these were Time to First Fixation, First Fixation Duration, Total Fixation Duration, and Fixation Count. Each of these metrics was analyzed with a 2 (group) * (6: emotion * 3: area of interest) mixed design ANOVA.

Time to first fixation

The ANOVA showed that there was a main effect of emotion on Time to First Fixation (F (3.51, 112.28) = 3.36, p = .016, η_p^2 = 0.10), and significant interactions between area of interest (AOI: eyes, nose and mouth) and emotion (F (10, 320) = 8.61, p = .001, η_p^2 = 0.21), and between AOI and group (F (1.47, 47.16) = 6.07, p = .009, η_p^2 = 0.16). The TBI group (M = 3.55) took significantly longer than the non-TBI group (M = 1.42) to initiate first fixation to the eyes (p = .002, d = 1.16) and looked at the nose first for all stimuli (p = .009, d = 1.05) for nose compared to eyes and (p = .003, d = 0.80) for nose compared to mouth. There was no significant main effect of group (F (1, 32) = 2.38, p = .133, η_p^2 = 0.07) and no main effect of AOI (F (1.47, 47.16) = 2.48, p = .109, η_p^2 = 0.07).

First fixation duration

There were no significant group-related differences for this eye tracking metric (all F values ≤ 1.91, all p *values* ≥ .109).

Total fixation duration

There was a main effect of AOI (F (2.22, 70.93) = 9.54, p = .001, η_p^2 = 0.23) and a main effect of emotion (F (3.90, 124.71) = 4.31, p = .003, η_p^2 = 0.12) but no significant main effect of group (F (1, 32) = 2.21, p = .147, η_p^2 = 0.07) on Total Fixation Duration. There was Results also showed interactions between AOI and emotion (F (8.54, 273.26) = 12.63, p = 001, η_p^2 = 0.28) and AOI and group (F (2.22, 70.93) = 4.76, p = .004, η_p^2 = 0.13). Compared to the non-TBI group (M = 0.69), the TBI group (M = 1.16) spent significantly longer fixating on the nose (p = .006), whereas the non-TBI group (M = 2.48) fixated more on the eyes (p = .013) compared to the TBI group (M = 1.36).

Fixation count

Results of analyses of total fixation counts showed significant main effects of AOI (F (1.28, 41.07) = 12.01, p = .001, η_p^2 = 0.27), emotion (F (4.41, 141.24) = 13.12, p < .001, η_p^2 = 0.29), and group (F (41, 32) = 9.43, p < .004, η_p^2 = 0.23). There were also significant interactions for AOI and emotion (F (6.10, 195.29) = 18.85, p < .001, η_p^2 = 0.35) and between AOI and group (F (1.28, 41.07) = 12.86, p < .001, η_p^2 = 0.29). The interactions between emotion and group (F (4.41, 141.24) = 0.30, p = .893, η_p^2 = 0.01) and between AOI, emotion, and group (F (6.10, 195.29) = 1.75, p = .110, η_p^2 = 0.05) were both non-significant. Simple effects analyses of the interaction between AOI and group showed that there were significant differences between the two groups for number of fixations to the eyes (p < .001, η_p^2 = 0.35, means of 7.38 and 2.89, respectively, for the non-TBI and TBI groups) and to the nose (p = .040, η_p^2 = 0.13, means of 2.47 and 3.52, respectively, for the non-TBI and TBI groups), there was no significant difference between the groups in number of fixations on the mouth (p = .671, η_p^2 = 0.01, means of 2.63 and 2.37, respectively, for the non-TBI and TBI groups).

Table 4. Means and standard deviations (SD) for time to first fixation (seconds), first fixation duration (seconds), total fixation duration (seconds), and fixation count (number) for TBI (N = 17) and non-TBI group (N = 17) on the static stimuli task.

		Anger		Disgust		Fear		Happy		Sad		Surprised	
		TBI	*Non-TBI*	*TBI*	*Non-TBI*	*TBI*	*Non-TBI*	*TBI*	*Non-TBI*	*TBI*	*Non-TBI*	*TBI*	*Non-TBI*
Time to first Fixation (Seconds)	**Eyes**												
	Mean	2.98	1.43	4.14	1.79	2.99	1.24	4.17	1.58	3.70	1.22	3.33	1.25
	SD	2.48	1.03	2.38	1.75	2.37	1.43	2.58	1.30	2.85	1.12	2.49	1.44
	Nose												
	Mean	2.00	2.41	1.77	2.12	1.74	2.93	2.44	2.94	1.61	2.37	2.24	2.99
	SD	1.51	1.27	1.53	1.33	1.47	1.55	1.83	1.60	1.08	1.51	1.57	1.56
	Mouth												
	Mean	4.05	4.06	2.30	2.20	3.22	2.58	2.90	2.69	3.65	3.61	3.62	3.06
	SD	2.58	2.36	2.28	1.56	2.15	2.05	2.73	2.08	2.81	2.54	2.69	2.03
First Fixation Duration (Seconds)	**Eyes**												
	Mean	0.30	0.31	0.37	0.25	0.25	0.33	0.32	0.29	0.31	0.30	0.38	0.30
	SD	0.23	0.13	0.42	0.07	0.17	0.11	0.30	0.23	0.24	0.09	0.39	0.13
	Nose												
	Mean	0.31	0.23	0.36	0.27	0.31	0.22	0.28	0.19	0.29	0.27	0.29	0.21
	SD	0.34	0.08	0.21	0.08	0.12	0.09	0.19	0.09	0.12	0.14	0.15	0.07
	Mouth												
	Mean	0.27	0.22	0.30	0.32	0.29	0.29	0.37	0.32	0.29	0.23	0.27	0.25
	SD	0.18	0.14	0.17	0.15	0.17	0.13	0.30	0.18	0.21	0.14	0.20	0.13
Total Fixation Duration (Seconds)	**Eyes**												
	Mean	1.64	2.64	1.00	2.05	1.45	2.67	1.00	1.92	1.33	2.76	1.71	2.81
	SD	1.56	1.25	1.04	1.28	1.31	1.38	1.06	1.20	1.29	1.38	1.49	1.35
	Nose												
	Mean	1.14	0.67	1.19	0.82	1.32	0.77	0.91	0.54	1.31	0.79	1.06	0.55
	SD	0.70	0.37	0.52	0.33	0.66	0.58	0.65	0.29	0.57	0.54	0.80	0.27
	Mouth												
	Mean	0.67	0.69	1.49	1.34	0.87	1.17	1.42	1.23	0.98	0.90	0.93	1.03
	SD	0.63	0.84	1.07	1.05	0.67	1.02	0.97	0.85	0.91	0.92	0.88	1.02
Fixation Count	**Eyes**												
	Mean	3.29	7.54	2.16	6.35	3.42	8.14	1.97	5.90	3.08	8.16	3.40	8.19
	SD	2.18	3.95	1.85	3.78	2.33	4.69	1.80	3.34	2.59	4.21	2.60	4.67
	Nose												
	Mean	3.57	2.49	3.59	2.76	4.17	2.58	2.58	2.16	3.89	2.71	3.32	2.12
	SD	2.09	0.92	2.29	0.88	2.04	1.28	1.55	1.01	2.05	1.14	2.17	1.00
	Mouth												
	Mean	1.71	1.79	3.04	3.31	2.26	2.83	2.84	3.03	2.11	2.22	2.27	2.59
	SD	1.39	1.79	1.94	1.96	1.62	1.95	2.00	2.11	1.68	2.03	1.78	1.88

Summary of experiment 1

Overall, the group with TBI showed different eye scan patterns when viewing static faces compared to the non-TBI group. The non-TBI group typically generated first fixation to the eyes, whereas those with TBI mostly fixated on the nose in the first instance. Those with TBI displayed longer first fixation durations across all emotions, suggesting that they had a more protracted eye scan pattern compared to the non-TBI group. The non-TBI group had the longest overall fixation duration for the eyes consistently followed by the mouth and then the nose. The group with TBI displayed slightly shorter *total* fixation latencies across the whole task compared to non-TBI. The non-TBI group had the longest overall fixation duration for the eyes consistently followed by the mouth and then the nose. The non-TBI group had a higher number of fixations to the eye region compared to the TBI group for all emotions, whereas the opposite pattern was observed for the nose region.

Experiment 2: Dynamic task

Table 5 presents means and standard deviation for the accuracy of identifying each emotion for the TBI and non-TBI group on the dynamic emotion recognition task.

Data in Table 5 show that scores for the Happy stimuli were approximately the same for both groups as the static experiment, indicating that this emotion was easier to identify than the other emotions.

Table 5. Mean, standard deviations *(SD)*, significance (*p),* and effect size (Cohen's *d*) for the number of emotions correctly identified for TBI and non-TBI group for the dynamic task.

ADFES emotion stimulus	TBI Group mean (*SD*)	Non-TBI Group mean (*SD*)	*p*	*d*
Anger	4.28 (2.02)	5.72 (0.57)	.006	1.11
Disgust	3.94 (1.55)	5.39 (1.20)	.004	1.05
Fear	3.44 (1.62)	4.78 (0.94)	.005	1.05
Happy	5.94 (0.24)	6.00 (0.00)	.324	0.50
Sad	4.78 (0.81)	5.06 (0.73)	.286	0.36
Surprise	5.72 (0.67)	6.00 (0.00)	.087	0.84
Overall total score	28.39 (4.50)	32.89 (2.22)	< .001	1.34

Descriptive data indicated that people with TBI were most accurate at identifying Happy, Surprise, and Sad stimuli in that order, whereas for non-TBI that pattern was Happy and Surprise followed by Anger for dynamic task stimuli.

Emotion labeling accuracy

Descriptive data indicated that the TBI group scored lower than the non-TBI group, particularly for negative emotions. Furthermore, the TBI group showed greater performance variability compared to the non-TBI group indicated by the large standard deviations, predominantly during the identification of Anger, Fear, and Disgust stimuli. The same analyses were used for dynamic data as static data.

Results of ANOVA showed a significant main effect of group (F (1, 34) = 18.88, p = .001, η_p^2 = 0.36), and emotion (F (3.58, 121.87) = 18.85, p = .001, η_p^2 = 0.36), and a significant interaction of emotion and group (F (3.58, 121.87) = 4.10, p = .001, η_p^2 = 0.11). Pairwise comparisons showed that those with TBI were less accurate at identifying Angry (p = .006), Disgust (p = .004), and Fear (p = .005) faces compared to the non-TBI group during the dynamic unfolding of an emotion.

Time to first fixation

Results of analyses showed no significant main effects (all Fs ≤ 1.51, all ps ≥ .051, all η_p^2 ≤ 0.84) but there was a significant interaction between AOI and emotion (F (10, 340) = 6.50, p < .001, η_p^2 = 0.16), indicating that time to first fixation for each AOI varied, depending upon the emotional stimulus viewed. Examination of this interaction with simple effects analyses revealed that for the eyes compared to the nose AOI only for the Happy face was there a significant difference with participants fixating quicker on the eyes (p = .04, d = 0.64; for the non-significant comparisons all ps ≥ .128, d ≤ 0.54). For the eyes versus mouth comparisons only Anger, Fear, and Surprise faces were significant with participants fixating more quickly on the eyes (ps ≤ .037; ds ≥ 0.86; for non-significant comparisons all ps ≥ .162, ds ≤ 0.55). Finally, for the nose versus mouth comparisons again, Anger and Fear were significant, with participants fixating quickest on the nose (ps ≤ .034; ds ≥ 0.45; for non-significant comparisons all ps ≥ .058, ds ≤ 0.46). Means and SDs for all eye-tracking metrics can be seen in Table 6

First fixation duration

As with static task data, there were no main effects or interactions (all F values ≤2.55, all ps ≥ .064). It is possible that this metric is less sensitive than the others – a consideration for future studies.

Total fixation duration

Results of ANOVA showed a main effect of AOI (F (1.50, 50.96) = 6.36, p = .007, η_p^2 = 0.16) and emotion (F (2.28, 48.33) = 5.19, p < .001, η_p^2 = 0.13), and an interaction between AOI and emotion (F (4.09, 176.21) = 3.15, p = .015, η_p^2 = 0.09). To further investigate the interaction between AOI and emotion, simple effects analyses were conducted. The findings indicated that participants fixated for longer on the eyes compared to the nose for all emotions (all ps ≤ .012, all ds ≥ 0.95) except for Sad (p = .059, d = 0.73), fixated longer on the eyes than the mouth for Anger, Disgust, and Fear (all ps ≤ .045, ds ≥ 0.74; the non-significant ps all ≥ .055, all ds ≤ 0.79), and fixated longer on the mouth than the nose for Disgust and Happy faces (ps of .048 and < .001 and ds of 0.51 and 1.16, respectively; all non-significant ps ≥ .256, ds ≤ 0.33).

Fixation count

There was a significant main effect of AOI (F (1.20, 40.95) = 6.89, p = .009, η_p^2 = 0.17) and emotion (F (5, 170) = 9.76, p < .001, η_p^2 = 0.22), but no significant main effect of group (F (1, 34) = 3.61, p = .066, η_p^2 = 0.10). The AOI and emotion interaction was the only significant interaction (F (5.10, 173.46) = 12.02, p < .001, η_p^2 = 0.26). Examination of this interaction with simple

Table 6. Means and standard deviations (SD) for time to first fixation (seconds), first fixation duration (seconds), total fixation duration (seconds), and fixation count (number) for TBI (N = 18) and non-TBI group (N = 18) on the dynamic stimuli task.

		Anger		Disgust		Fear		Happy		Sad		Surprised	
		TBI	*Non-TBI*	*TBI*	*Non-TBI*	*TBI*	*Non-TBI*	*TBI*	*Non-TBI*	*TBI*	*Non-TBI*	*TBI*	*Non-TBI*
Time to first Fixation (seconds)	**Eyes**												
	Mean	1.58	1.25	2.35	1.41	1.98	1.35	1.96	1.57	2.23	1.70	1.68	1.32
	SD	1.32	1.19	1.66	1.29	1.19	1.26	1.22	1.35	1.23	1.62	1.39	1.40
	Nose												
	Mean	1.94	1.89	2.04	1.80	1.81	2.22	2.18	2.40	2.03	2.04	1.62	2.13
	SD	1.54	1.15	1.45	0.84	1.31	1.12	1.22	0.77	1.26	0.83	1.16	1.25
	Mouth												
	Mean	3.16	2.46	2.32	1.77	2.75	2.34	2.30	1.83	2.80	2.33	2.64	2.17
	SD	1.67	1.55	1.42	1.17	1.69	1.52	1.39	1.22	1.59	1.67	1.67	1.47
First Fixation Duration (seconds)	**Eyes**												
	Mean	0.12	0.28	0.20	0.21	0.30	0.27	0.24	0.22	0.24	0.22	0.20	0.22
	SD	0.20	0.22	0.16	0.11	0.19	0.20	0.16	0.18	0.20	0.13	0.14	0.16
	Nose												
	Mean	0.36	0.35	0.22	0.36	0.28	0.39	0.28	0.27	0.25	0.37	0.36	0.26
	SD	0.25	0.57	0.10	0.48	0.20	0.75	0.19	0.17	0.13	0.51	0.23	0.37
	Mouth												
	Mean	0.25	0.33	0.28	0.39	0.26	0.28	0.51	0.42	0.30	0.36	0.28	0.29
	SD	0.25	0.24	0.20	0.23	0.19	0.19	0.45	0.28	0.23	0.26	0.22	0.21
Total Fixation Duration (seconds)	**Eyes**												
	Mean	1.61	2.14	1.73	2.17	1.29	1.90	1.21	1.82	1.13	1.55	1.53	1.74
	SD	1.18	1.59	1.38	1.63	0.95	1.48	1.03	1.66	1.02	1.36	1.21	1.49
	Nose												
	Mean	1.14	0.85	0.99	0.93	0.95	0.77	0.89	0.73	0.89	0.81	0.77	0.96
	SD	0.88	0.88	0.72	0.55	0.66	0.81	0.56	0.52	0.56	0.61	0.55	0.83
	Mouth												
	Mean	0.59	1.10	1.15	1.44	0.72	1.19	1.46	1.72	0.91	1.22	0.95	1.02
	SD	0.66	1.10	0.89	0.98	0.66	1.12	1.05	1.15	0.92	1.08	0.10	0.90
Fixation Count (number)	**Eyes**												
	Mean	4.00	6.36	2.36	4.60	3.33	6.36	3.59	5.79	2.86	4.85	4.01	6.14
	SD	2.01	4.91	2.11	3.75	2.55	5.29	3.15	5.21	2.56	4.22	2.01	5.11
	Nose												
	Mean	3.00	2.38	2.97	2.56	2.93	2.14	2.73	2.12	2.66	2.32	3.09	2.15
	SD	2.44	1.19	2.08	1.23	1.94	1.03	1.75	1.24	1.72	1.00	1.81	1.38
	Mouth												
	Mean	1.41	2.44	2.41	3.09	1.87	2.81	2.82	3.59	1.85	2.57	1.89	2.93
	SD	1.35	1.90	1.57	1.84	1.64	2.23	1.79	2.42	1.45	2.02	1.62	2.19

effects analyses revealed that for all emotions except Disgust participants fixated more times on the eyes than on the nose (all significant ps $\leq .044$, ds ≥ 0.73; Disgust $p = .225$, $d = 0.41$), for all emotions except Disgust and Happy participants fixated more times on the eyes compared to the mouth (all significant ps $\leq .035$, ds ≥ 0.84; non-significant ps $\geq .098$, ds ≤ 0.62) and for the nose versus mouth comparisons for Angry faces participants fixated more times on the nose compared to the mouth ($p = .027$, $d = 0.48$), whereas the reverse pattern was observed for Happy faces ($p = .033$, $d = 0.52$), all the other comparisons were non-significant (all ps $\geq .359$, ds ≤ 0.21).

Summary of experiment 2

The analyses of the eye-tracking data (see Table 6) show that there were no differences between the TBI and non-TBI groups in the patterns of fixations on the eye, nose, and mouth AOIs. Where there were significant effects, the tendency was for participants to attend faster and longer to the eye regions compared to the nose and mouth regions, however, there was rather a mixed pattern of findings across the different emotions in this regard. Similar to the static task, the TBI group had significantly poorer emotion recognition ability.

Discussion

Our findings showed that those with TBI were less accurate overall on emotion recognition judgments compared to the non-TBI group on the static task. They also took significantly longer than the non-TBI group to respond to stimuli, but this slower latency did not translate to greater accuracy in the TBI group. On the dynamic task, the TBI group was less accurate at

identifying negative emotions than the non-TBI group during the unfolding of an emotion. Importantly, those with TBI showed atypical eye scan patterns during emotion identification in static task compared to non-TBI group and showing a tendency to focus on the nose and the lower part of the face.

Both groups were least accurate at identifying Fear and most accurate at identifying Happy faces when presented with static emotional faces (Liao et al., 2013). Importantly, the TBI group was significantly slower to correctly recognize emotional stimuli than the non-TBI group. It remains to be determined whether this lag represents slower cognitive processing overall or atypical and uninformative eye scan patterns. However, eye tracking data suggest some potential causative factors in the present study.

On the dynamic task, negative emotional stimuli, Angry, Disgust, and Fear produced the least accurate responses in the TBI group. It is plausible that these findings might translate to real-world contexts as they were a response to more *real-life* stimuli than the static faces. The diminished ability to accurately judge negative emotions from static and dynamic stimuli could represent a serious handicap for the TBI group when negotiating social situations, particularly given the negative valence of these emotions. Usually, these emotional expressions engage muscles in the upper half of the face, and it may be this factor that is the problem for those with TBI rather than the emotion portrayed, indicating visual hypometria for eye fixation/face scanning. However, it should be noted that there were no group differences for the eye-tracking metrics in the dynamic task.

The eye tracking data support the notion of disruption to normal scan patterns for faces in the TBI group for static stimuli. Those with TBI focused first on the nose for all emotional stimuli in the static task, whereas the non-TBI group looked at the eyes first for all stimuli. The nose is arguably the least informative part of the face, even the nose scrunch of disgust tends to wrinkle the upper part of the nose close to the eyes. The significantly different eye scan patterns of TBI group compared to non-TBI group potentially explain lower accuracy scores on the static task. This was a surprising finding. Other work has shown an absence of eye fixation in those with TBI when viewing emotional faces but not the preferential fixation to the nose.

Oatley (2014) used an eye tracking task with the aim of identifying mechanisms underlying face emotion perception difficulties after head injury. They recruited seven male TBI participants with moderate-to-severe brain injury and a non-TBI group. Eye movements were recorded during viewing of static images for both groups. The TBI group fixated significantly less on the eyes across all emotions compared to those without TBI during the self-paced task – similar to findings presented here. It is not known whether they fixated more on the nose instead of the eyes. Our finding might contribute to a better understanding of why there is diminished eye fixation after brain injury because our data show that the focus is on the nose instead in our group potentially indicating visual hypometria for eye scan patterns.

In the dynamic task, the TBI group performed similarly to the non-TBI group. This pattern was not consistent with that of the static task where there were marked differences between the groups in the eye-scanning patterns. The capacity of those with TBI to look at the eyes for the emotional stimuli in the dynamic task across the whole task before responding indicates that other eye tracking data could not be explained as eye avoidance, use of conscious or unconscious strategy for gaze aversion away from the eyes or central screen fixation bias. It is difficult to explain from these data why there should be differences in eye-scan patterns for the static task but not for the dynamic task. It is plausible though that moving stimuli facilitated eye-movements to more appropriate face feature on the dynamic task because kinematic information is known to provide an independent contribution to emotion recognition (Sowden et al., 2021).

Historically there is a long-established pattern between oculomotor change, gaze patterns, and brain injury. Samadani et al., (2015) reported that disconjugate gaze and abnormal eye scan patterns have been detected in those with brain injury since antiquity. Findings presented here support the notion of an association between TBI, eye scan disruption on static emotional stimuli and emotion judgment accuracy. Repeated fixation counts to the nose for negative static stimuli in those with TBI are perplexing. Most knowledge about neural mechanisms underpinning visual fixation comes from oculomotor data, less is known about mechanisms underpinning altered patterns, and the limited evidence comes from the neurobiology of reading. Zhang et al. (2021) proposed that the neural basis of first fixation to any stimulus is associated with the primary visual cortex and extra-striate cortex located in the occipital lobe. However, this system, in the case of emotion recognition, must come on stream after initial oculomotor activation. Arguably, the possibility of disrupted attentional shift and/or deficient oculomotor control post-TBI fits better with findings of the present study. However, distinguishing the neural correlates of these mechanisms is problematic because they are fundamental to many other cognitive processes – making it difficult to distinguish precise linear mechanisms. Both attentional shifts and oculomotor control are

associated with a network known as the *eye movement control* network that includes the frontal eye field (FEF), supplementary eye field (SEF), and intraparietal sulcus (Esterman et al., 2015). It is a robust, large-scale network with connectivity to early visual pathways (Zhang et al., 2021).

Meghanathan et al. (2020) proposed that working memory and executive functions contribute to first fixation to target. According to this theory, fixations involve encoding information into visual working memory whilst refixations (fixation count) are considered to involve updating of information or rehearsal, presumably this is the *executive* contribution. What we need to distinguish moving forward, is whether these higher cognitive processes are brought into play very early on in visual processing of emotion from facial stimuli in TBI and non-TBI groups. This will help to determine whether the problem post-injury lies with the higher cognitive functions (well known to be impaired after brain injury) or within the oculomotor and eye movement control network or a combination of both. If it is the case that first fixations are part of a strategic operation, blending front-first with learned information, and that refixations function to update visual working memory, then visual working memory, in those with TBI, may be receiving faulty information from the eye movement control network.

The processes responsible for the neurobiology of emotion recognition are known to be complex and multimodal, requiring synthesis of information from multiple neural systems. Unfortunately, they are only defined in piecemeal fashion in humans. To date, we know that brainstem, midbrain, and vestibular systems are important for initiating first fixations through oculomotor signals (Sparks, 2002). Findings from animal studies have shown that neurons in the interstitial nucleus of Cajal (NIC), and vestibular nuclei (located in pons and medulla) fire during vertical saccades, and lesions to the NIC impair ability to maintain vertical and torsional eye position in monkeys (Helmchen et al., 1996). It is possible that some version of this process, emerging as fixation hypometria, might be occurring in those with brain injury who are failing to fixate above the nose for many facial stimuli, particularly when static. Additionally, it is also likely that there are (potentially small) derangements in multi-modal systems important for emotion recognition in natural circumstances after severe TBI. The introduction of motion in the dynamic task draws on the visual pursuit system, which maintains the image of the object on or near the fovea. Our findings intimate that motion may have had a beneficial effect for more typical eye-movements for the TBI group in the dynamic task.

Rucci and Poletti (2015) commented that fixational eye movements are the ultimate token of behavior necessary for normal vision (pg. 501). Eye fixations transform the stimulus transmitted to the retina into a spatiotemporal signal that is suited to neural processing (Rucci & Poletti, 2015). Thus, if the fixation rests on an uninformative part of the face, the nose for example, then the information conveyed to the retina and visual system is similarly uninformative. Our findings suggest that aberrant eye fixation mechanisms might contribute to the emotion recognition impairments seen after TBI. This possibility combined with damage to ventral cortices (BA 47), a hub for emotional processing (Sprengelmeyer et al.,1996, 1998) vulnerable to head injury, and dysregulation of the eye movement control network and possibly higher cognitive functions (executive and working memory processes), might prove a first step in a new explanation of emotional and social deficits post-TBI.

Demographically, TBI and non-TBI groups were matched for age, sex, and years of education, but those with TBI fell below the non-TBI group on IQ measures. This finding is typical post-TBI and usually indicative of a significant and severe brain injury (Wood & Rutterford, 2006). Importantly, those with TBI had IQ scores that fell within the low average, not the impaired range, and we were not using experimental tasks designed to specifically index IQ abilities in the present study. Almost all of the TBI group had severe head injuries based on conventional clinical assessment – (16 out of 17 people – Static and 16 out of 18 – Dynamic). Thus, findings of the present study reflect the effects of severe brain injury on emotion recognition tasks. In addition, although specific lesion data were absent in many cases, most had frontal pathology based on clinical evaluation. Reduced Verbal IQ mean score post-injury also points to frontotemporal pathology. That said, lesions and cause of injury were heterogeneous in the TBI group (see Appendix A) and participants were approximately 8–9 years post-injury, so results are indicative of chronic long-term effects of injury.

Limitations

Our sample size was relatively small, so we retained a significance level of 0.5 for all analyses to balance against a potential lack of power, and future work might include larger samples and more conservative sig levels. There were some differences in our two tasks, for example, mode of responding, and this should be addressed in future work. Additionally, precise lesion data would have enabled analyses of

which brain regions and functional pathways were damaged in patients.

Conclusions

In the present study, we found poorer emotion recognition performance in both the static and dynamic tasks along with aberrant eye scan patterns in the static task in those with TBI compared to non-TBI. Findings suggest potential disruption to oculomotor systems vital for first stage perceptual processing and associated with lower accuracy on behavioral measures. It is plausible that these impairments diminish adaptive social functioning and rehabilitation might usefully target retraining of facial emotion recognition in those with TBI, perhaps using conscious visual strategies to overcome hypometria and/or potential *mid-flight* oculomotor abnormalities. Establishing the functional basis of emotion recognition deficits after TBI will contribute to the development of evidence-based rehabilitation programs and potential new research avenues to address intractable problems with social cognition post-injury.

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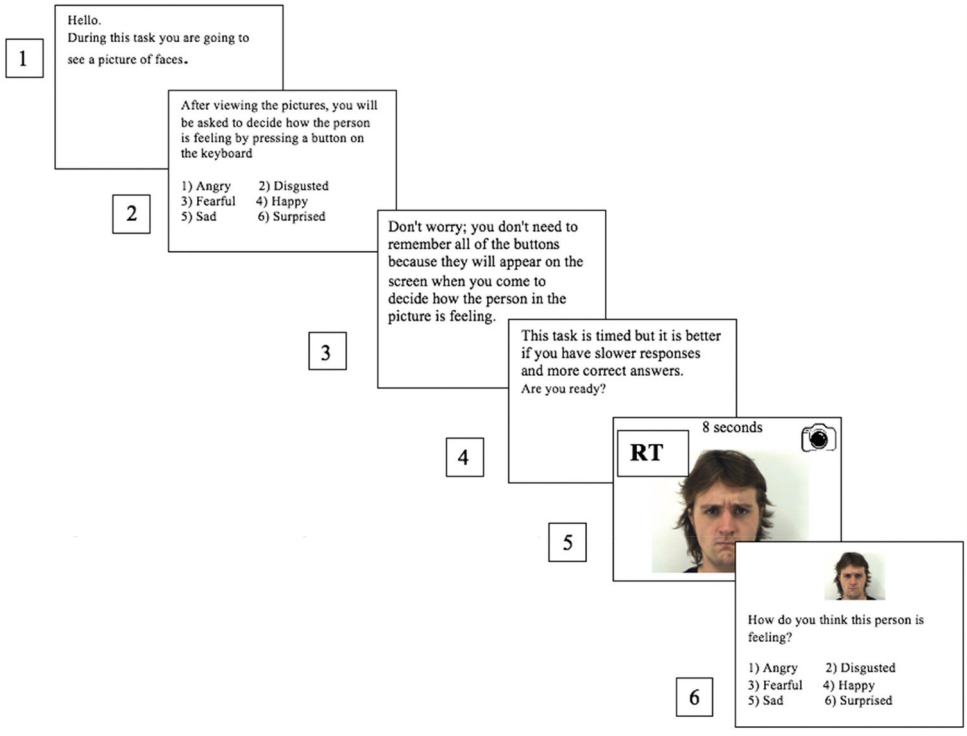
Appendix A.
Demographic and clinical characteristics of TBI participants (*n* = 18)

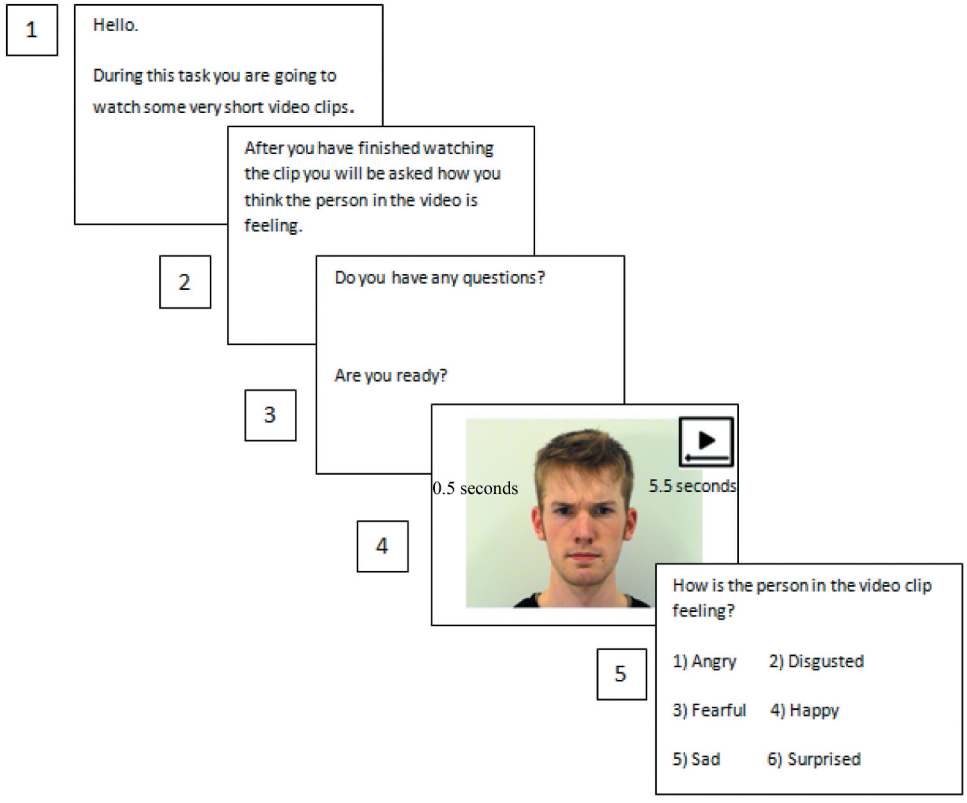
Key: Frontal lobe pathology (FLP); pathology which does not encroach on either frontal lobes or occipital cortex but may be present in other cortical or subcortical brain regions (O); road traffic accident (RTA).

Participant Code	Gender	Age	Injury Location	Injury Severity	Years Post-Injury	Mechanism of Injury
1	Male	26	O	Severe	7	Assault
2	Male	40	FLP	Severe	21	RTA (car)
3	Male	53	FLP	Severe	15	Fall
4	Male	54	O	Severe	30	RTA (car)
5	Female	33	O	Mild	10	Fall from horse
6	Female	60	O	Severe	29	RTA (car)
7	Male	47	O	Moderate	16	RTA (motorbike)
8	Male	28	FLP	Severe	11	Assault
9	Male	50	FLP	Severe	5	Fall (unconfirmed)
10	Male	31	FLP	Severe	1	Assault
11	Male	63	FLP	Severe	4	RTA (pedestrian)
12	Male	43	FLP	Severe	3	Fall from scaffold
13	Male	33	O	Severe	16	Fall from seizure
14	Male	60	FLP	Severe	3	Fall downstairs
15	Male	53	FLP	Severe	2	Fall
16	Female	47	FLP	Severe	1	Fall
17	Male	39	FLP	Severe	4	Assault
18	Male	59	FLP	Severe	1	Cyclist (collision with car)

Appendix B

Static task: The sequence of events for the Static task. The facial stimulus appeared for eight seconds before automatically moving onto the answer screen. Eye tracking metrics and RT data were collected during screen five.
Dynamic: Sequence of events for the Dynamic Task. The participant would indicate when they had read the instructions and the researcher would move the test along by pressing the spacebar. The video lasted for 6 seconds before automatically moving onto the answer screen. Only eye tracking data collected during screen four was analyzed.




1
Hello.
During this task you are going to watch some very short video clips.
After you have finished watching the clip you will be asked how you think the person in the video is feeling.
2
Do you have any questions?
Are you ready?
3
0.5 seconds
5.5 seconds
4
How is the person in the video clip feeling?
1) Angry
2) Disgusted
3) Fearful
4) Happy
5) Sad
6) Surprised
5