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Brain Injury

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Dear Prof. Thomas F. Bergquist,

We sincerely thank you and the reviewers for your careful review and constructive feedback.

Following the comments, we have conducted a thorough review of the manuscript to correct the typos and remove references to tables that were not displayed properly.

We hope these corrections meet your expectations.

Once again, we thank the editor and reviewers for their detailed and precise review.

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Involvement of physiological reactivity and interoception in emotional experience after a traumatic brain injury

Abstract

Objective

Emotional experience is based, among other factors, on physiological reactivity (PR) and the awareness of this reactivity corresponding to interoception. After a traumatic brain injury (TBI), patients exhibit reduced PR and interoception, raising questions about the integrity of their emotional experience.

Method

To examine this issue, 26 men with moderate to severe TBI (age: 37 ± 11) and 26 ~~men~~ healthy male controls (age: 35 ± 14) watched emotional films (amusement, tenderness, anger, disgust). PR was measured via electrodermal activity (EDA) and heart rate variability (HRV). After each film, an emotional evaluation was completed using the Differential Emotional Scale (DES). Interoception was measured through a heartbeat counting (HBC) task and the Multidimensional Assessment of Interoceptive Awareness (MAIA) questionnaire.

Results

Compared to controls, TBI participants scored lower on the MAIA Emotional Awareness and Noticing subscales, and exhibited lower EDA and HRV during the anger and tenderness films. However, emotional evaluations and HBC task scores were similar between groups. Positive correlations were found between emotional evaluation and the MAIA scale.

Conclusion

These results suggest a dissociation between emotional experience and PR after TBI and decreased interoceptive sensitivity. Since interoception links PR and emotional experience, exploring the impact of reduced interoception on this dissociation could improve our understanding of post-TBI emotional functioning.

Keywords: Traumatic brain injury, emotion, electrodermal activity, heart rate variability, interoception

1. Introduction

The implication of bodily changes and their perception, referred to as interoception, in emotion has been discussed for more than a century. According to the first major peripheralist theory by James and Lange (1), emotion emerges from the perception of bodily changes, including facial expressions (crying, smiling, blinking), and PR (heart rate, sweating, etc.), elicited by the emotional stimulus, which are at the origin of the subjective emotional feeling. Since the James-Lange theory, this view has been debated by centralist theories, which postulate that bodily changes are caused by subjective feelings resulting from the cognitive evaluation of the stimulus (2). According to this view, bodily changes occur quite simultaneously with emotional experience without one causing the other (2). Subsequently, Damasio's somatic marker hypothesis highlights the role of the perception of somatic states in emotional reasoning and interpersonal relationships (3). According to this hypothesis, the prefrontal cortex records somatic states experienced during each emotional experience called "somatic markers", which can later guide behaviour when similar situations arise. This theory, inspired by the famous case of Phineas Gage who after a severe TBI developed emotional behavioural disorders similar to an 'acquired sociopathy', underscores the importance of bodily changes and interoception in emotions. While their role remains debated (4), investigating these two points is essential for understanding the emotional process, especially in the TBI population in which emotional disorders are frequently observed (5).

Moderate to severe TBI frequently damages the prefrontal cortex and its connections with limbic and posterior regions such as the insula (6), leaving TBI patients vulnerable to emotional disorders (7). These disorders, present in 62% of patients one year after TBI, affect daily functioning, socio-professional reintegration, and quality of life (8,9). These difficulties include emotion regulation disorders, emotional lability, indifference, irritability, and a reduced ability to experience emotional states, such as sadness or fear (10,11,12) and alexithymia, which refers to difficulties in emotional awareness or diminished abilities to recognise one's feelings (13,14). Additionally, the degree of impairment in subjective emotional experience is correlated with the severity of social behavioural problems (15). Several researchers have hypothesised that abnormalities in PR may underlie these emotional issues in TBI (16,17,18).

The PR reflects autonomic activity under the control of the autonomic nervous system (ANS). The ANS regulates automatic body functions, such as cardiovascular activity, sensory systems and glands to maintain internal homeostasis and help the body adapt to environmental changes. The ANS is controlled by a neuronal system composed of the hypothalamus, the limbic system, and the frontal lobe area~~s~~ (19). It comprises two branches: the sympathetic nervous system (SNS) which mobilises the body for fight or flight responses, and the parasympathetic nervous system (PNS), which restores the body to a resting state. Activation of the ANS produces changes in ~~the~~ heart rate (HR), heart rate variability (HRV), and electrodermal activity (EDA). HRV refers to the variation in the time interval between heartbeats, influenced by the SNS and PNS. At rest, the PNS predominates, slowing down the HR, while during stress, the SNS accelerates HR, and the PNS then restores the balance through deceleration of the HR. These rapid variations in HR frequency demonstrate the ANS's ability to adapt to its environment (20). HRV can be measured using time-domain methods, such as the standard deviation of interbeat intervals (SDNN), and the root-mean-square of interbeat intervals (RMSSD), or frequency-domain methods, which differentiate between SNS and PNS contributions. The low-frequency (LF) component of HRV represents both parasympathetic and sympathetic activity, while the high-frequency (HF) component reflects the parasympathetic influence (21). Higher HRV is associated with better emotional regulation (22). After a TBI, lower HRV has been reported (23, 24) and associated with impaired emotional and social functioning (25). More generally, impairments in PR are frequently reported after a TBI and are coherent given the anterior location of the lesions. Several studies have reported reduced startle blinks, EDA, and facial reactivity to emotional pictures and movies (26,27,28, for review:29).

In parallel, the ability to detect bodily changes also appears to decline after a TBI as patients presented lower scores on the heartbeat perception interoceptive accuracy task (30). More generally, interoception seems to decrease after a frontal injury (31, 32, 33). Interoception refers to the processes by which an organism senses, interprets, and integrates signals from within itself and below the skin, involving both top-down and bottom-up mechanisms (34). *Interoceptive accuracy*, the ability to accurately perceive physiological signals, is generally measured with a heartbeat counting (HBC) task (35). In this task, participants silently count their heartbeats at rest during different time intervals, and their counts are then compared to the actual heartbeats. *Interoceptive sensibility* refers to the subjective perception of one's ability to detect or discriminate body signals and is measured using self-report questionnaires. One of the most used questionnaires is the Multidimensional Assessment of Interoceptive Awareness (MAIA) questionnaire (36), which allows for the measurement of different interoceptive dimensions. Interoception plays a major role in emotional processes as higher interoceptive ability is associated with stronger affective experiences (37). Participants with higher interoceptive perception exhibit increased cardiac reactivity and more intense emotional ratings of film clips (38,39). Additionally, superior interoceptive accuracy on the HBC has been reported as enhancing theory of mind (TOM) task performance (40). Emotional disorders after frontal acquired injury have also been linked to lower interoception. Hynes et al. (30) emphasized the connection between reduced interoceptive accuracy and alterations in emotional awareness following TBI. Adolfi et al. (30) found that damage to the fronto-insular region leads to reduced interoception, emotional processing, and social cognition and proposed a shared corticosubcortical network involving the insula for the processing of interoceptive, emotional, and social information. Finally, according to Desdentado et al. (31), interoception plays a role in explaining alexithymia and emotional regulation after acquired brain injury.

According to the Jamesian perspective, PR and interoception contribute to the emergence of emotional experience. As PR and interoception appear to be reduced after a TBI, the first goal of the current study is to investigate the lack of emotional experience after TBI. Secondly, it is of prime interest to examine the relationship between ~~the~~ emotional experience, PR and interoception in a TBI group compared to a demographically matched healthy group. Based on existing literature, the following hypotheses are proposed. First, consistent with previous research, it is hypothesized that the TBI group would report lower emotional experience during emotional film clips compared to the control group (11). Second, PR during clips is expected to be lower for the TBI group than for the control group (for review: 29). Third, we expect that interoceptive accuracy and sensibility would be lower following TBI (30). Finally, it is proposed that interoception will be related to emotional experience regardless of the presence of TBI.

2. Methods

2.1. Participants

Considering the gender influence frequently reported with emotional material (41,41) and the prevalence of TBI in men (43), our sample is exclusively composed of men.

2.2. TBI group

26 men with moderate to severe TBI participated in the study. The severity of TBI was determined based on a self-report questionnaire completed by the participants. They were at least 2 years post-injury with no identified aphasia or agnosia. They had no prior history of psychiatric, neurological, or developmental disorders. TBI participants were aged 22 to 59 years ~~old~~ (Mean (M) age= 37.5 years, Standard Deviation (SD) = 11.9). The time post-injury ranged from 2 to 34 years (M=12.19 years, SD=9.66). 23 participants had ~~have~~ undergone rehabilitation, one participant ~~during~~ for less than a month, five participants for between 3 and 9 months, two participants for between 9 months and one year, and fifteen participants for more than one year. Rehabilitation included kinesitherapy for 21 participants, speech therapy for 16, neuropsychology for 21, psychotherapy for 15, and occupational therapy for 21. TBI participants had on average completed 11.42 years of education (SD=2.25). Before the injury, 15~~fifteen~~ participants had been employed, 7 ~~seven~~ were still in school and four were unemployed. At the time of recruitment, 5 ~~five~~ TBI participants had a job. Finally, 12 ~~twelve~~ participants reported experiencing emotional sequelae since their TBI.

2.3. Control group

26 men participants aged from 21 to 65 years ~~old~~ (M=35.7, SD=14.2) participated in ~~to~~ the study. Control participants had on average completed 12.38 years of education (SD=2.27). They did not have any history of developmental, neurological, or psychiatric disorders. The results of independent samples t-tests indicated no significant difference between TBI and control groups for education level ($t(42.78)=-1.45$, $p=.16$), and age ($t(48.47)=0.49$, $p=.63$).

2.4. Questionnaires and task

Behavior Rating Inventory of Executive Function

To measure the emotional sequelae after TBI, the subscales of Emotional Control and Self-Monitor from the Behavior Rating Inventory of Executive Function (BRIEF; 44) were proposed to TBI participants. These two subscales contain 16 ~~-~~items describing problems related to executive dysfunction consequences on emotional behaviour and self-control. To measure the changes due to TBI, we modified the items by adding ~~added the modifying the items to include~~ the words “Since the injury,” at the beginning of each of them. For instance, the first item of the Emotional Control subscale was: “Since the injury, I have had fits of anger”. Each item is rated using a three-point frequency scale (1=never, 2~~,~~ sometimes, 3=often).

The hospital anxiety and depression scale

Anxiety and depression symptoms were evaluated using t~~T~~he Hospital Anxiety and Depression Scale (HADS;45; French validation: 46). This scale contains 14 items divided into two dimensions: seven items for depression and seven for anxiety. The score for each item ranges from zero to three, with a maximum score of 21 for each dimension. A total score of 11 or more can indicate the presence of anxiety or depressive symptoms.

Frontal Assessment Battery

Executive functions were screened with t~~T~~he Frontal Assessment Battery (FAB; 47). The battery is composed of six subtests exploring (1) conceptualization and abstract reasoning (similarities test); (2) mental flexibility (verbal fluency test); (3) motor programming and executive control of action (Luria motor sequences); (4) resistance to interference (conflicting instructions); (5) inhibitory control (go–no go test); and (6) environmental autonomy (prehension behaviour). Each subtest is rated from 3 (better score) to 0, for a maximum score of 18. A score under 16 can indicate the presence of executive dysfunction.

Toronto Alexithymia Scale

Alexithymia was evaluated using the 20-i~~I~~tems Toronto Alexithymia Scale (TAS-20) developed by Bagby et al. (48) (French validation by Loas et al. (49)). The TAS-20 is a self-report questionnaire comprising 20 items rated on a Likert scale from 1 (completely disagree) to 5 (completely agree). The scale is divided into three subscales that evaluate ~~aimed at evaluating~~ the primary dimensions of alexithymia: Difficulty Identifying Feelings (DIF), Difficulty Describing Feelings (DDF), and Externally Oriented Thinking (EOT). A score greater than or equal to 56 classifies a subject as alexithymic. ~~indicates that subjects are considered alexithymic.~~

MAIA questionnaire

The interoceptive sensibility was assessed using the French version of the MAIA questionnaire ([version 2, MAIA-2] 50, French validation by Da Costa Silva et al. (51)). The MAIA-2 is a 37 items questionnaire designed to evaluate eight facets of interoceptive body awareness: (1) *Noticing:* awareness of uncomfortable, comfortable, and neutral body sensations; (2) *Not-distracting*: tendency not to be distracted by oneself from sensations of pain or discomfort; (3) *Not-worrying*: tendency not to worry with sensations of pain or discomfort; (4) *Attention regulation*: ability to sustain and control attention to body sensation; (5) *Emotional Awareness*: awareness of the connection between body sensations and emotional states; (6) *Self-regulation*: ability to regulate psychological distress by attention to body sensations; (7) *Body listening*: actively listening ~~listens~~ to the body for insight; and (8) *Trusting*: experiences one own's body as safe and trustworthy. Each item is scored on a Likert scale from 0 (never) to 5 (always). The score for each of the eight subscales is calculated by averaging the scores of the items belonging to the respective subscale.

HBC task

The HBC task (35) measures the cardiac interoceptive accuracy using ~~under~~ electrocardiogram (ECG) recordings. In this task, participants were requested to count their own heartbeats during intervals of 25, 35 and 45 seconds. After each interval, the participants reported the number of heartbeats without taking their pulse or trying to guess it. The adapted instructions outlined by Desmedt et al. (52), emphasizing the necessity of reporting solely their perceptually felt heartbeats, were implemented. The beginning and the end of each interval were notified with a tone. The number of heartbeats was then counted using the BIOPAC data analysis packages (AcqKnowledge 5.0 software). The total score was calculated by comparing the heartbeats reported by the participant with the heartbeats recorded using the following formula: $\frac{1}{3} \times \sum\left(1 - \left(\frac{heartbeats\ recording - heartbeats\ reported}{heartbeats\ recording}\right)\right)$ (35). The total score varies between 0 (low interoceptive accuracy) and 1 (high interoceptive accuracy).

2.5. *Emotional films*

We selected four films from the FilmStim database (53) because their elicitation properties had been validated. This database comprises 64 film excerpts selected by 50 experts and evaluated across various dimensions by 364 undergraduate students. Specifically for anger, we chose video number 2 (code 12), a 115-second excerpt from the film *Schindler's List* (Spielberg, 1993). Additionally for amusement, we selected video 8 (code 18), a 144-second excerpt from the film *Les 3 frères* (Bourdon & Campan, 1995). For disgust, v~~V~~ideo 35 (code 45), a 104-second excerpt from *Trainspotting* (Boyle, 1996), was also chosen. Lastly, for tenderness, we picked video number 15 (code 15), a 121-second excerpt from the film *Forrest Gump* (Zemeckis, 1994).

2.6. Emotional evaluation

The emotional experience during films was assessed using the DES developed by Izard et al. (54) and adapted by McHugo et al. (55) (validated in French by Philippot (56)). The DES evaluates discrete emotional dimensions and consists of 16 items. Each item comprises groups of adjectives as follows: 1) *interested, concentrated, alert*; (2) *joyful, happy, amused*; (3) *sad, downhearted, blue*; (4) *angry, irritated, mad*; (5) *fearful, scared, afraid*; (6) *anxious, tense, nervous*; (7) *disgusted, turned off, repulsed*; (8) *disdainful, scornful, contemptuous*; (9) *surprised, amazed, astonished*; (10) *warm-hearted, gleeful, elated*; (11) *loving, affectionate, friendly*; (12) *guilty, remorseful*; (13) *moved*; (14) *satisfied, pleased*; (15) *calm, serene, relaxed*; (16) *ashamed, embarrassed*. Beneath each item, a 7-point Likert scale (1 = "not at all", 7 = "very intense") is presented. To ensure that participants reported their actual feelings during the films and not what they anticipated the films would evoke in most people, the following instruction was presented before each emotion evaluation: "Your answers should reflect how you really felt during the extract, not how most people would feel about it. Report how you felt at the precise moment of the extract and not your general mood of the day.".

2.7. Physiological measures

PR was measured with ECG and skin conductance measurements using the data acquisition system MP160 BIOPAC System (Inc, Goleta, CA, USA). ECG data were recorded with disposable 8-mm Ag/AgCl ECG electrodes (Kendall H66LG, Medtronic, Ireland) placed over the participants' clavicles and at the ~~left~~ lower left ribs. Given the minimum time requirement for HRV analysis (57) and the 30-seconds duration of the film's interval of interest (IOI), the RMSSD time-domain index was used as the HRV measure. RMSSD was derived from the ECG signal using the BIOPAC data analysis packages within the AcqKnowledge 5.0 software. Skin conductance level (SCL) was measured on the non-dominant hand with two disposable 27mm Ag/AgCl EDA electrodes (Biopac Systems EL507A, Goleta, CA, USA) placed on the index and middle fingers.

2.8. Procedure

Participants first completed the questionnaires. TBI participants filled out the TAS-20 and completed the FAB. Both TBI and control participants completed the HADS and the MAIA scales. After the first phase, participants were seated at a table in front of a computer and ECG and EDA electrodes were applied. Data from ECG and EDA were recorded during a two-minutes baseline and for the entire duration of the task. Following the baseline, the HBC task was administered. Subsequently, the four film clips were presented, and after each clip, participants completed the 16 items from the DES. The entire session lasted approximately one hour. The procedure is illustrated in **Figure 1**. Ethical approval for this study was obtained from the Ethics Committee of Erasme Hospital (Free University of Brussels) on August 27,2021 (Protocol Reference: P2021/300, CCB B4062021000180).

[INSERT Figure 1]

2.9. Data reduction and analysis

For the purposes of this study, we focus on the SCL and ECG recordings obtained during a specific interval of interest (IOI) - namely, the 30-seconds segment of the film clip that most strongly evoked the target emotion. This IOI was determined by two independent judges. To enhance data quality and minimize artefacts, a high-pass filter of 1 Hz was applied to the ECG data, while a low-pass filter of 1 Hz was applied to the EDA data. HRV, particularly the time-domain measure of the RMSSD, was extracted from both the IOI and the baseline using AcqKnowledge 5.0 software. For the EDA data, SCL was calculated for each IOI and baseline using AcqKnowledge 5.0 software. To standardize the EDA and RMSSD data, IOI data were subtracted from baseline data, followed by a log transformation to normalize the data. Due to the extreme values of RMSSD data, one TBI participant and one control participant were excluded from the HRV analysis.

Data analysis was conducted using R software (version 4.2.2) and the RStudio interface. After verifying the assumption of variance homogeneity with Levene's test, two-tailed, independent-sample t-tests using the rstatix package (58) were performed to examine differences in questionnaires (HADS and MAIA) and HBC tasks between groups. P-values were adjusted using the false discovery rate procedure (59) with the stats package (R Core Team, 2022) to control for the probability of making Type I errors due to multiple comparisons.

For the film analyses, firstly to ensure that the films elicited different emotional feelings, a 4x16 repeated-measures ANOVA was conducted with the four films as the independent variable and the 16 DES items as the repeated dependent variable. Secondly to examine the differences between groups, the scores of the DES items corresponding to the emotion elicited by each film, i.e. *joyful, happy, amused* items for the amusement film; *angry, irritated, mad* items for the anger film; *disgusted, turned off, repulsed* items for the disgust film and *moved* items for the tenderness film were compared between both groups. This was done using four separate two-way ANOVAs, with "Group" and "DES items" as dependent variables and the values of these items as independent variables. Thirdly similarly to Schaefer et al. (53) analysis, the accuracy of the emotional evaluation for each film in each group was examined using paired t-tests comparisons between the DES items for each film separately. More specifically, for each film, a set of 4 predefined paired t-tests contrasting the target items and each non-target items were computed for each group. Meaning for the films evoking anger and disgust, the target DES items were *fearful, scared, afraid* and *disgusted, turned off, repulsed* compared to 4 non-target items, which were *joyful, happy, amused*; *warm hearted, gleeful, elated*; *moved* and *satisfied, pleased*. For the films of tenderness and amusement, the target items were *moved* and *joyful, happy, amused,* the non-target items were *sad, downhearted, blue*; *angry, irritated, mad; fearful, scared, afraid* and *disgusted, turned off,* *repulsed*. Due to the large sample size and the large number of planned comparisons, we decided to apply Bonferroni corrections for multiple comparisons.

For the PR analyses, to explore group differences for SCL and RMSSD, two separate two-way ANOVAs were conducted. In each ANOVA, “Films” and “Group” were specified as dependent variables, while SCL or RMSSD served as the independent variables. If the ANOVA was significant, post hoc paired comparisons with Tukey adjustments were then conducted to explore group differences for the same film. As there is variability in the time post-injury in our TBI group, we investigated its potential influence with correlation analyses. Still in the TBI group, we performed correlation analyses between the TAS-20 total scale and the MAIA total scale. In both groups, correlation analyses were also performed between emotional evaluation scores and MAIA total scores. As the data are ordinal, Spearman’s correlation was used (Spearman’s rho; 60). Control~~s~~ and TBI participants were then grouped according to their MAIA total score into two groups. Total sample percentiles based on MAIA scores were calculated. Participants at or below the 49^{th} percentile were in the “lower interoceptive group” and participants above the 49^{th} percentile were in the “higher interoceptive group”. The lower group was composed of 16 TBI and 9 control participants, the higher group was composed of 10 TBI and 17 control participants. Chi-squared analysis revealed an independence between the grouping according to the level in the MAIA scale and the presence or absence of a TBI (χ^2 = 2.77, p-value = 0.10). There were no significant differences between the lower and higher MAIA groups for age ($t(49.09)=0.75$, $p=.45$) and education~~al~~ level ($t(42.78)=-1.45$, $p=.16$). The emotional evaluation of these two groups was then compared using two-tailed independent-sample t-tests. Finally, in the TBI group, we investigated whether the level of emotional and cognitive difficulties, as well as time post-injury, could be related to emotional evaluations of the films. Correlation analyses were performed between DES items and FAB~~BREF~~, HADS, TAS-20, HBC task, BRIEF and time since injury.

3. Results

3.1. *Questionnaires and HBC task*

For the BRIEF, the TBI group obtained a mean score of 1.76 (SD=0.48, range=1.1-2.8) on the Emotional Control subscale and 1.72 (SD=0.61, range=1-2.8) on the Self-Monitoring subscale, suggesting that, on average, most of our TBI participants sometimes struggle with emotional and self-monitoring difficulties since the injury. The mean FAB score of 15.3 (SD=2.15, range=11-18), suggests the presence of executive dysfunction in 13 of the participants. On the TAS-20, they had a mean score of 57.2 (SD=10.19, range=32-74), indicating that 19 TBI participants presented alexithymia. No differences were observed between the TBI and healthy control groups for measures of depression, anxiety, and the HBC task. Lower interoceptive sensibility was observed for the Emotional Awareness ($t(46.57)=-3.39$,

p=.013, FDR corrected) and Noticing (t(48.75)=-2.79, p=.033, FDR corrected) MAIA subscales (See **Table 1**).

[INSERT Table 1]

3.2. Emotional evaluation

Firstly, a 4 × 16 repeated-measures ANOVA showed a significant interaction between film category and DES items (F(42, 3052)=31.59, p<.001), indicating that the self-reported emotional profile was modulated by film category.

Secondly, the comparison between groups with the two-way ANOVA revealed no main effect of group (F (1,200) =1.255, p=0.264), of items (F (3,200) =2.041, p=.109), or interaction between groups and items (F (1,200) =0.186, p=0.9). The mean scores for each item and group are displayed in **Table 2**. Average scores ranging from 3.85 to 5.15 indicate a medium to high level of emotion, considering that the DES scale ranges from 1 (not at all) to 7 (very intense).

[INSERT Table 2]

Thirdly, the four paired t-tests comparisons between the target and non-target DES items for each film were significant in both groups, confirming that the films induced the targeted emotion in both groups.

3.3. Physiological responses

EDA

A two-way ANOVA on the logarithm of SCL values revealed a main effect of group (F(1,47) = 5.59, p = 0.0223), of films (F(3,141) = 2.893, p = 0.0375) and an interaction between group and films (F(3,141) = 2.978, p= 0.0337). Post-hoc analysis revealed lower SCL in the TBI group compared to the control group for the anger (estimate = -0.1631, SE = 0.053, t(170) = -3.078, p = 0.0024, Tukey corrected) and the tenderness (estimate = -0.1274, SE = 0.053, t(170) = -2.404, p = 0.0173, Tukey corrected) films (See **Figure 2**).

[INSERT Figure 2]

HRV

A two-way ANOVA on the logarithm of RMSSD values found a marginal mean effect of group (F(1,48) = 3.966, p = 0.0521) and no effect of films (F(3,144) = 2,123, p = 0.099) and no interaction between group and films (F(3,144) = 2.058, p = 0.1085). Post-hoc analysis revealed lower RMSSD in the TBI group compared to the control group for the anger film (estimate = -0.2970, SE = 0.114, t(95.6) = 2.617, p = 0.0103, Tukey corrected) and the tenderness (estimate = -0.2465, SE = 0.114, t(95.6) = 2.171, p = 0.032, Tukey corrected) film (See **Figure 3**).

[INSERT Figure 3]

3.4. Correlational analyses

In the TBI group, correlation analyses with time post-injury revealed a positive correlation with HBC task scores (rho = 0.48, p = .056). Partial correlation between HBC task scores and time post-injury, controlling for cognitive influence using the FAB scores, revealed a stronger positive correlation (rho = 0.51, p =.052). Additionally, in the TBI group, the correlation measurement between the scores on the TAS-20 and the MAIA total showed a significant negative correlation (rho = -0.54, p < .001).

The correlation between the MAIA total score and the DES items corresponding to each film showed a positive relationship between the MAIA and the tenderness items for each group, analysed separately. A significant positive correlation for the amusement items was found in the TBI group, and this correlation was marginally significant in total the sample. For the anger and the disgust films, the correlation did not reach significance (See **Table 3**).

[INSERT Table 3]

Analyses according to the level of interoception in the MAIA scale were conducted for the tenderness and the amusement films. The higher interoceptive group rated more intensely the amusement (t (47.768) = -1.879, p = .066) and the tenderness (t (47.768) = -2.0465, p = .046) experienced during the amusement and tenderness films, respectively, compared to the lower interoceptive group.

Finally, for the correlation analyses between the emotional evaluation of each film and the HBC task, the emotional and cognitive questionnaires and the time post-injury, the only significant correlations were observed for the emotional evaluation of the disgust film. This was positively correlated with the Self-Monitoring BRIEF subscale (rho = 0.50, p = 0.015) and negatively correlated with the HBC task (rho = -0.45, p = 0.022).

4. Discussion

The aim of this study was to examine the role of PR and interoception in emotional experience after a TBI. Emotional experience was induced with films, and interoception was measured using an HBC task and the MAIA scale. Contrary to our hypothesis, the TBI group did not differ in their emotional evaluation of the films. However, in line with our hypothesis, PR was lower in the TBI group, especially for the tenderness and anger films. The TBI group obtained lower scores than the control group on the HBC task, but the result was not significant. Interestingly, in the TBI group, HBC task scores were positively correlated with the time post-injury, even when controlling for the influence of cognitive deficits. Additionally, lower interoceptive sensibility was observed in the TBI group on the Emotional Awareness and Noticing subscales of the MAIA scale. The total MAIA scale score was positively correlated with the emotional evaluation of the tenderness film. Finally, analyses according to the level of interoceptive sensibility showed more intense emotional evaluation in the higher interoceptive group compared to the lower interoceptive group for tenderness and amusement films. In this discussion, we address the lack of difference between groups in emotional evaluation despite lower PR in the TBI group considering the peripheralist (1) and the centralist (3) conceptions of emotion. We then discuss the role of interoception in this dissociation between PR and emotional evaluation in the TBI group. Additionally, we explore why PR is specifically weaker in response to the anger and tenderness films. Finally, we discuss the validity of interoception measurements.

First contrary to our assumptions, we found no difference in emotional evaluation between groups suggesting a preserved subjective emotional experience in TBI participants even if their PR was reduced for anger and tenderness films. The peripheralist perspective (1) considers that PR predicts emotional experience. Therefore, according to this perspective, the emotional evaluation of the anger and tenderness films should have been reduced in TBI group. The fact that disrupting PR does not necessarily impact emotional experience argues against the peripheralist theory and supports centralist and appraisal theories. Centralist theories argue that bodily responses are not required for emotional experience while appraisal theories claim that emotional experiences stem not only from the representation of immediate bodily states but also from cognitive assessments involving value judgments and semantic knowledge (e.g.,61). Some patients' data are consistent with this assumption of dissociation between PR and emotional experience. Soussignan et al. (26) observed lower facial muscle contraction and SCL in response to pleasant and unpleasant visual and olfactory stimuli in a patient with frontotemporal damages due to a TBI compared to a control group. However, his emotional experience seemed to be preserved as no difference was observed for the pleasure and arousal rating of stimuli. Osborne-Crowley et al. (62) found that participants with TBI were able to empathize with the emotional stories of others despite having markedly reduced SCL. Moreover, Johnsen et al. (63) found that patients with damage to the ventromedial prefrontal cortex presented lower skin-conductance responses (SCR) in response to music but generated normal judgments of their subjective feelings in response to music. Conversely, patients with damages to the right somatosensory cortex presented lower self-rated feelings in response to music but showed normal SCRs to music. Regarding their results and according to the neuroanatomical theoretical framework previously described by Damasio and Adolphs (64), the authors suggested a double dissociation between ~~for~~ emotional autonomic responses ordered by the prefrontal ventromedial cortex and subjective emotional experience produced by the somatosensory cortex. In the absence of PR, due to prefrontal injuries as frequently observed after TBI (6), the emotional experience could only rely on a cognitive assessment of the films as proposed by the appraisal theories.

Another explanation for this dissociation between PR and emotional experience could be found in the preservation or lack of interoception. The current constructivist view of emotion embodied by the Conceptual Act Theory (65) suggests that emotional experience emerges from four dimensions: the core affect based on interoceptive sensations, the exteroceptive sensations which include the five senses (audition, vision, olfaction, gustation, touch), the conceptual knowledges which are the episodic and the semantic knowledges, and the executive functions. These four components combine within a given context to create an emotional experience. On the one hand, we may hypothesize that if interoceptive abilities are effective, individuals can consider bodily responses, along with the three other components to construct their emotional experience. In non-clinical populations, interoception has been linked to the intensity of emotional experiences (66). Specifically, interoception influences the connection between bodily responses and emotional experience, as demonstrated by Dunn et al. (66) ~~study~~. The study found that participants who could more accurately perceive their heartbeat had a stronger correlation between their HR reactions and their subjective evaluation of emotional images. Some of our results are consistent with the idea that interoception moderates ~~of moderation of~~ emotional experience ~~by interoception~~, as we found a positive correlation between interoceptive sensibility and the emotional evaluation of all films except for the disgust film, as well as more intense emotional evaluations in the higher interoceptive group for tenderness and amusement films. On the other hand, in the case of lower interoception, as found in our TBI participants, emotional bodily responses may not be considered in the construction of emotional experiences, which could rely on other components such as the conceptual knowledges activated by the stimuli. Our data are insufficient ~~clearly not sufficient~~ to verify this hypothesis. However, our TBI group presented alexithymia, reflecting a lack of emotional awareness despite similar emotional evaluations of films ~~similar to that of~~ to the control group. We found a negative correlation between interoceptive sensibility and alexithymia in the TBI group, suggesting that poor emotional awareness is associated with lower interoceptive sensibility. Moreover, authors consider alexithymia as a general deficit of interoception as it is associated with poor self-reported non-affective interoception (67). In the case of emotions induced by films, this lack of emotional awareness, possibly linked to a lack of interoception, could be offset by conceptual knowledge linked to the films, explaining the lack of difference between the groups in the emotional evaluation of the films. Indeed, compared to other methods of emotional elicitation, films are cognitively complex and may prime cognitions in addition to those related to the emotion (68). However, this hypothesis needs to be investigated experimentally to be verified.

Lower PR were found in the TBI group for tenderness and anger films but not for amusement and disgust films. This result for the anger film might appear contradictory to findings that TBI patients are more likely to exhibit heightened anger responses (69) and show increased SCL during anger recall compared to healthy controls (70). However, a distinction must be made between exaggerated anger responses due to a lack of inhibition (71) and socially mediated anger elicited by films which relies on TOM abilities. Indeed, tenderness and anger films involve stronger interpersonal characters compared to disgust and amusement films. Emotions such as anger and tenderness may be less accessible for individuals with TBI, as they involve understanding the interpersonal situation and sharing another person's experience in this interaction. This relies on TOM skills, referring to the ability to infer or reflect on the content of one's own and others' mental states (72), and on empathy. Tenderness has been defined as empathic feelings, as experiencing tenderness towards someone requires perceiving their vulnerability or attachment to another person, which relies on empathy (73). The selected tenderness film for this study, which depicted a father and son reunited, could elicit feelings of tenderness through identification and understanding of the characters' emotions. The anger film selected showed a concentration camp commander who randomly shot ~~shoots~~ prisoners from his balcony. Anger elicited by the excerpt could rely on empathy for the victim but also on understanding the commander's motivation and more generally on feelings of injustice. The emotional elicitation of these two emotions therefore relies ~~therefore~~ on empathic and TOM abilities, which are reduced after TBI (10). Lower empathy after TBI has been associated with lower facial muscle contraction, SCL, HR, and emotional evaluation of film clips (17, 18). Interestingly, de Sousa et al. (28) presented happy and angry facial expressions to TBI participants; compared to control participants, TBI participants with lower empathy abilities showed reduced facial muscle responses and SCR to anger but not to happy faces. In the current study, the purpose was not to investigate empathy after TBI, but in the future, it would be interesting to investigate the influence of empathy on PR for different kinds of emotions such as anger and tenderness.

Contrary to our assumptions, we did not find a difference in interoceptive accuracy on the HBC task between groups. Although the TBI participants' scores were lower than those of the control group, the difference did not reach significance. Interestingly, we found a positive correlation between HBC scores and time post-injury, suggesting a possible recovery of interoceptive accuracy over time. This is consistent with previous research showing an improvement in self-awareness over ~~with~~ time since ~~post-~~injury after TBI (74, 75). If there is indeed a recovery of interoceptive accuracy, the 12 years post-injury time frame of our TBI sample could explain the lack of significant difference with the control group. Indeed, in the study by Hynes et al. (30), lower interoceptive accuracy on a heartbeat discrimination task was found for TBI participants with an average post-injury delay of 6 years. However, the lack of results for the HBC task should be qualified by the fact that the validity of the task has been questioned, as it relies on non-interoceptive processes such as subjective beliefs about heart frequency or time estimation (52). Even though we used adapted instructions that stressed the importance of reporting only perceptually felt heartbeats, reducing the contribution of guessing strategies, this reduction depended on participants' compliance with these instructions (76). Additionally, certain non-interoceptive factors such as body mass index, systolic blood pressure, and age can still influence scores (52). Therefore, future research should propose new valid interoceptive accuracy tasks by focusing on signals that are more consciously detectable and easily modifiable in a non-invasive manner than cardiac signals. In addition to increasing the validity of the tasks, focusing on other modalities could provide a more complete picture of interoceptive accuracy, as it is increasingly accepted that interoceptive accuracy could be modality-specific. According to the modern view of interoceptive accuracy (77), each interoceptive modality carries specific information to the organism (e.g., dyspnea, gastric perception), which may not be equally relevant for survival, representing distinct subjective sensations. The information from each modality is then evaluated in low-level and automatic processes before being integrated into a "whole-body pattern," giving rise to behavioral or verbal reports of these sensations. General interoceptive ability would therefore be an integration or combination of all possible interoceptive modalities. For all these reasons, future studies should develop new tools across different modalities. This is why we have created a new respiratory interoception task, adapted to a TBI population (78).

Our results may have some clinical implications for patient therapy. They suggest that following TBI, the construction of emotional experience no longer relies on bodily cues, as both PR and interoceptive sensibility are reduced. In the context of emotion induction through films, as in our study, we hypothesise that this reduction in bodily information could be compensated by components related to conceptual knowledge. However, in everyday life, patients report persistent emotional sequelae. We hypothesise that the lack of bodily information in the construction of emotional experience may contribute to the persistence of emotional difficulties. We believe that patient therapy should incorporate methods that enhance bodily information and interoception. For instance, HRV biofeedback can increase HRV by training individuals to breathe at the typical resonant frequency of six cycles per minute (79). This method has shown beneficial effects for TBI patients, improving not only HRV but also emotional functioning (80). Moreover, mind-body interventions such as meditation, yoga and mindfulness have shown promising results in the TBI population (81). However, research in this area is still in its early stages, and the effectiveness and underlying mechanisms of these approaches require further investigation.

Our study presented some potential limitations. Firstly, as mentioned earlier, the range of time post-injury in our TBI sample is wide. However, all our TBI participants are at least 2 years post-injury, which minimizes the influence of spontaneous recovery (82). Moreover, this wide variability of the time post-injury enabled us to identify a positive relationship between this time and ~~the~~ interoceptive accuracy, which may suggest recovery of interoception years after the TBI. This hypothesis remains to be verified and should be tested in future studies. Secondly, unfortunately, we did not have access to neuroimaging data from the patients with TBI, which limits the connections we can establish between our findings and lesion localisation. In future studies, it will be crucial to obtain precise information on lesion localisation, for instance, through structural MRI. Additionally, analyses using diffusion tensor imaging will be useful to examine connectivity between regions. Thirdly, due to the high prevalence of TBI in the male ~~man~~ population (83,84) and the influence of gender on emotional processing, we chose to include only men in our study. This decision has enabled us to neutralise a potential gender effect on our results, as men exhibited lower PR than women (85,86), and higher performance in cardiac interoceptive tasks, but reported paying less attention to body sensations compared to women in interoceptive self-reports (87).

Additionally, some studies on TBI patients have found that the female gender is associated with an increased risk of anxiety (88, 89,90) and mood disorders (91, 92), while others found no gender effect (93, 94, 95) or no persistent gender difference one-year post injury (96). However, while the inclusion of only men in our study reduces gender influence, the conclusions drawn from our results only apply to men. In future research, it would be interesting to replicate our study on women to determine whether our results can be generalised to the TBI population regardless of gender. Additionally, we did not have information about the ethnic demographics of the participants. As cultural context influences emotional responses (97) and interoception (98), this aspect should be controlled in future research. Finally, we used film clips to induce emotion. On the one hand, this could be considered a strength of our study as films have high ecological validity and are more dynamic than static pictures (99). Furthermore, we selected films from a validated database whose emotional elicitation power has been verified on a large sample (53). On the other hand, as mentioned previously, films involve complex cognitions which could trigger cognitive processes unrelated to the intended emotions. Additionally, films depict emotional situations that happen to others in a fictive setting (68), therefore the emotional elicitation of films relies on the TOM and empathy abilities of the participants. Finally, individual differences and previous experiences with the films might influence participants' responses to film clips (100,101). However, there is no perfect method to elicit emotion in a laboratory setting, and each method has its advantages and disadvantages that researchers need to be aware of and consider in data interpretation.

In conclusion, our study investigated the implications of PR and interoception in the emotional experience induced by films in individuals with TBI. Our findings suggest a dissociation between emotional experience and PR following TBI, with emotional experience being preserved but PR reduced. Additionally, individuals with TBI demonstrated lower interoceptive sensibility. These results challenge the peripheralist theory, which posits that PR is necessary for the construction of emotional experience. The dissociation observed after TBI may indicate that when PR and interoception are diminished, emotional experiences rely more on conceptual knowledge activated by the stimuli. Moreover, ~~since~~ considering how interoception ~~could~~ ensures the coupling between PR and emotional experience, it seems worthy to investigate how a decrease in interoception influences this dissociation to contribute to a better understanding of TBI emotional functioning.

5. Glossary

ANS: Autonomic nervous system

DES: Differential emotional scale

ECG: Electrocardiogram

EDA: Electrodermal activity

FAB: Frontal assessment battery

HADS: Hospital anxiety and depression scale

HBC: Heartbeat counting

HR: Heart rate

HRV: Heart rate variability

IOI: Interval of interest

MAIA: Multidimensional assessment of interoceptive awareness

PNS: Parasympathetic nervous system

PR: Physiological reactivity

RMSSD: Root mean square of successive differences

SCL: Skin conductance level

SCR: Skin conductance responses

SNS: Sympathetic nervous system

TAS-20: 20-Item Toronto Alexithymia Scale

TBI: Traumatic brain injury

TOM: Theory of mind

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8. Disclosure of interest

The authors report there are no competing interests to declare.

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Figure 1

Task procedure.

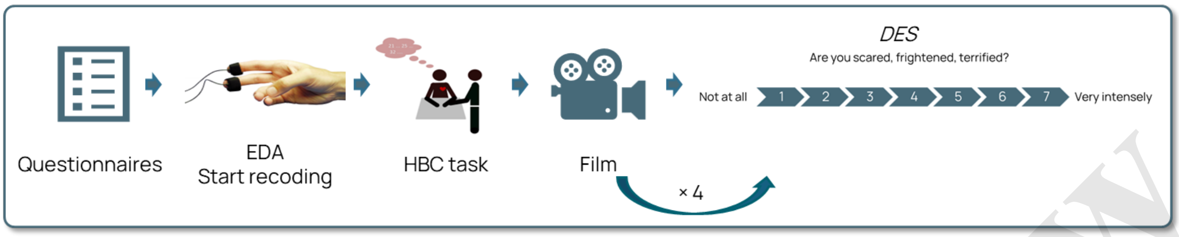

Figure 2

SCL during films for TBI and control groups.

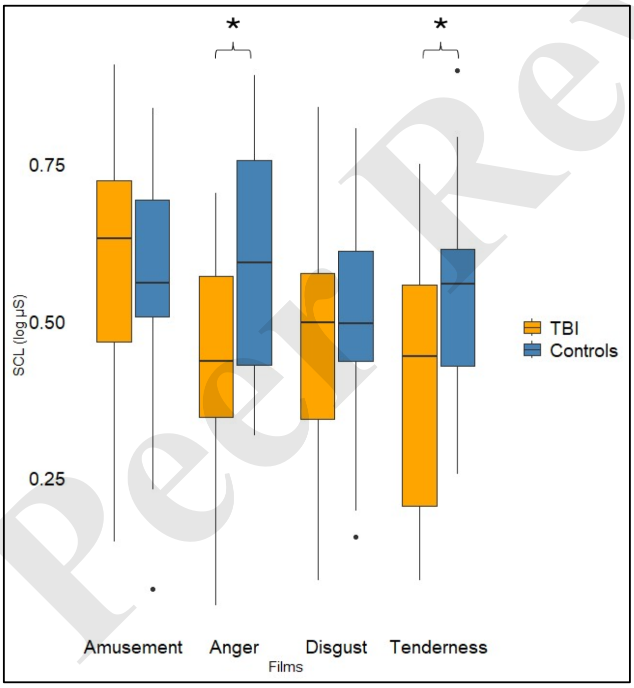

Figure 3

RMSSD during films for TBI and control groups.

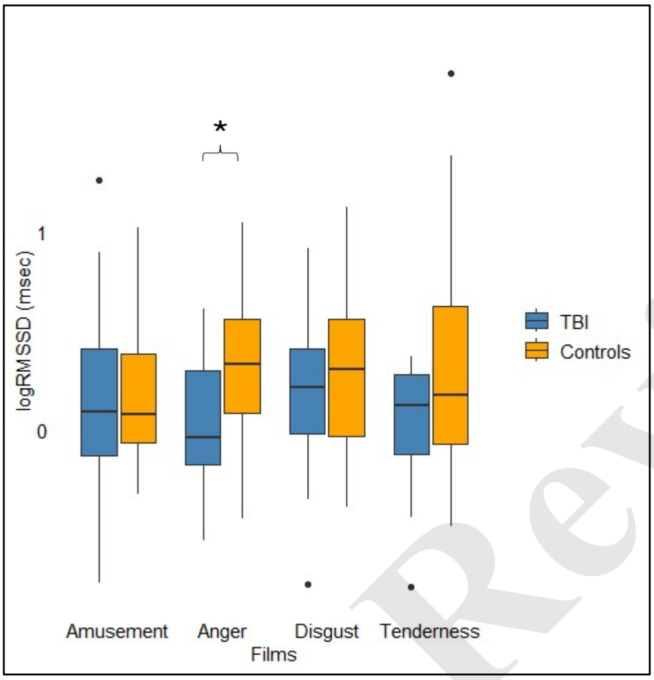

Table 1

Means, standard deviations, minimum, maximum and results of group comparisons for HADS, MAIA scales and HBC task.

	TBI			Controls			p-value
	Mean	SD	Min-Max	Mean	SD	Min-Max	Corrected FDR
HADS scale							
Depression	5.42	4.05	0-15	5.69	3.21	1-16	.792
Anxiety	7.73	4.18	1-17	6.96	4.09	0-15	.506
MAIA scale							
Self-Regulation	2.62	1.16	0.5-5	3.46	0.99	0.74-5	0.256
Trusting	2.19	1.19	0-5	1.67	1.02	0.62-4.33	0.699
Emotional Awareness	2.98	0.97	0.67-5	3.04	1.01	1.09-4.33	0.013*
Not-Distracting	2.46	1.34	0-4.86	2.92	0.93	0.53-4.57	0.212
Body Listening	3.05	1.15	0-5	4.02	0.87	0.89-5	0.635
Not-Worrying	2.51	1.53	0-5	3.06	1.31	1.11-5	0.824
Noticing	2.09	1.69	0-5	2.38	1.39	0.99-5	0.033*
Attention Regulation	3.59	1.49	0-5	3.78	1.19	1.24-5	0.256
Total MAIA	21.49	6.38	8.83-32.37	24.87	4.52	5.02-31	0.098
HBC task							
Total score	0.24	0.26	0-1	0.35	0.33	0-0.89	0.177

* Significant (p<.05) group difference

Table 2

Means and standard deviations for DES items corresponding to the film.

DES items	TBI	Controls
	Mean (SD)	Mean (SD)
Joyful, happy, amused	5.08 (2.10)	5.15 (1.46)
Angry, irritated, mad	4.23 (2.35)	4.23 (2.35)
Disgusted, turned off, repulsed	3.85 (2.17)	4.5 (2.12)
Moved	4.38 (2.25)	4.62 (1.79)

Table 3

Correlation between MAIA total scores and DES items for emotion target by the films

Measure	MAIA total	
DES Items	rho	P value
Amusement		
Total sample	0.25	.075
TBI	**0.41**	**.037***
Controls	-0.004	.984
Tenderness		

Total sample	**0.47**	**<.001***
TBI	**0.48**	**.013***
Controls	**0.36**	**.068#**
Disgust		
Total sample	-0.03	.818
TBI	**-0.37**	**.056#**
Controls	0.29	.145
Anger		
Total sample	0.24	.08
TBI	0.30	.126
Controls	0.04	.812

* Significant (p<.05) group difference
[#] Tendency toward significance