The Journal of Child Psychology and Psychiatry

Journal of Child Psychology and Psychiatry 59:12 (2018), pp 1289–1297 doi:10.1111/jcpp.12919

Neural reward responsiveness in children who engage in nonsuicidal self-injury: an ERP study

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Background: A better understanding of the correlates of nonsuicidal self-injury (NSSI) in children is important for the identification and prevention of future suicide risk. However, although abnormalities in reward responsiveness might constitute one potential transdiagnostic mechanism of risk for NSSI, no studies have examined initial response to reward in children with a history of NSSI. The goal of the present study was to address this important gap in the literature. To objectively assess initial response to reward, we utilized the feedback negativity (FN) event-related potential, a well-established psychophysiological marker of reward responsiveness. **Methods:** Participants were 57 children (19 with a history of NSSI and 38 demographically matched controls) between the ages of 7 and 11. Diagnostic interviews were used to assess for current and past DSM-IV mood and anxiety diagnoses and NSSI history. Children also completed a guessing task, during which continuous electroencephalography was recorded. **Results:** Children with a history of NSSI exhibited significantly more negative ΔFN (i.e., FN to losses minus FN to gains) than children without NSSI. These findings appeared to be at least partially independent of children's history of psychopathology and current symptoms, suggesting their specificity to NSSI. **Conclusions:** These results provide initial evidence for heightened neural initial reward responsiveness to losses versus rewards in children with a history of NSSI. Pending replications and longitudinal studies, the ΔFN might represent a psychophysiological marker of risk for self-harm.
Keywords: Nonsuicidal self-injury; rewards; event-related potential; children; feedback negativity.

Introduction

Nonsuicidal self-injury (NSSI) involves deliberate self-harm in the absence of intent to die (Nock, 2009, 2010). Research shows that approximately 7.6% of third graders (ages 7–9) and 4% of sixth graders (ages 10–12) report a lifetime history of NSSI (Barrocas, Hankin, Young, & Abela, 2012), with these rates increasing to approximately one in five in community samples of adolescents (Muehlenkamp, Claes, Havertape, & Plener, 2012). NSSI is associated with a significant number of negative outcomes including higher levels of emotional and interpersonal distress (e.g., Klonsky, Oltmanns, & Turkheimer, 2003) and impaired academic performance (Kiekens et al., 2016). In addition to the harm caused by NSSI itself, it is also a robust predictor of increased risk for suicide attempts (e.g., Joiner, Ribeiro, & Silva, 2012) and eventual death by suicide (for a review, see Hamza, Stewart, & Willoughby, 2012). Indeed, it has been suggested that NSSI might serve as a "gateway" to more serious and severe self-harming and suicidal behaviors (Whitlock et al., 2013). Therefore, although children typically engage in lower lethality self-harming behaviors compared to adolescents and adults, a better understanding of the correlates of NSSI in children specifically is crucial for the early identification and prevention of current and future suicide risk (Crowell & Kaufman, 2016).

It is also important to note that NSSI constitutes a transdiagnostic behavior, as it occurs across a variety of diagnoses including mood, anxiety, eating, personality, and substance use disorders (for a review, see Lofthouse, Muehlenkamp, & Adler, 2008), as well as in the absence of any diagnosable disorder (for a review, see Swannell, Martin, Page, Hasking, & St. John, 2014). To date, however, a large number of studies examining correlates of NSSI have done so in the context of a specific diagnosis, primarily borderline personality disorder (BPD; e.g., Brown, Comtois, & Linehan, 2002; Houben et al., 2017; Kleindienst et al., 2008; Zaki, Coifman, Rafaeli, Berenson, & Downey, 2013). Because this approach likely yields an incomplete picture, what is needed are studies that focus specifically on the behavior within a more heterogeneous sample. This type of approach is also consistent with the NIMH Research Domain Criteria (RDoC) initiative, which was explicitly designed to advance research and treatment by moving away from rigid diagnostic categories toward a more fine-grained, multimethod, and transdiagnostic approach to understanding a broad range of dimensions of normal and abnormal functioning.

One potential transdiagnostic mechanism of risk for NSSI is abnormalities in reward responsiveness. This is a broad construct that includes reward anticipation, initial response to reward, and reward satiation (National Advisory Mental Health Council Workgroup on Tasks and Measures for RDoC, 2016). Supporting this, developmental models of self-inflicted injury (SII), which include those who have engaged in NSSI and/or attempted suicide, suggest that these individuals tend to exhibit reward-related

Conflict of interest statement: No conflicts declared.

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deficits (e.g., Crowell, Derbidge, & Beauchaine, 2014; Crowell, Kaufman, & Beauchaine, 2014). In addition, a recent review suggests that numerous reward processing deficits, including impairments in reward learning and valuation, contribute to impaired decision-making in suicide attempters (Dombrovski & Hallquist, 2017). Consistent with these theories, research shows that anhedonia (i.e., loss of interest or pleasure in previously enjoyable activities), which is the most frequently investigated proxy of reward processing in individuals with self-harming thoughts and behaviors, is associated with self-injury (e.g., Ballard et al., 2016; Coryell & Young, 2005; Fawcett et al., 1990; Nock & Kazdin, 2002; Sadeh, Javdani, Finy, & Verona, 2011; Spijker, de Graaf, Ten Have, Nolen, & Speckens, 2010). Furthermore, there is also some evidence that NSSI is associated with impairments in the behavioral approach system (BAS; Gray, 1991), which regulates goal-oriented approach behavior, including responses to rewards. Specifically, hypersensitive BAS, assessed via the BIS/BAS Scale (Carver & White, 1994), has been positively linked with the occurrence and frequency of NSSI in adolescents (Burke et al., 2015) and young adults (Cerutti, Presaghi, Manca, & Gratz, 2012; Jenkins, Seelbach, Conner, & Alloy, 2013).

However, despite the important contributions of these studies, they have provided mixed evidence regarding the nature of reward processing deficits in individuals with a history of self-injury. Specifically, although the studies that focused on anhedonia suggest blunted reward responsiveness in those with SII, the studies that used the BIS/BAS Scale in individuals with NSSI suggest the opposite pattern of responding, a hypersensitivity to rewarding stimuli. Indeed, due to their reliance on self-reports that tap into multiple reward-related processes, these studies cannot differentiate between subconstructs of reward responsiveness. This represents a significant gap in the literature because anticipatory (i.e., reward anticipation) and consummatory (i.e., initial response to reward and reward satiation) reward processing are distinct processes with separable neural correlates (Liu, Hairston, Schrier, & Fan, 2011). An additional factor that may have contributed to previous mixed findings is the focus on individuals with SII, which includes those who have attempted suicide and/or engaged in NSSI, and few studies to date have examined reward processing abnormalities in NSSI specifically. This type of investigation is important, however, because of the large number of differences between NSSI and suicidal behavior (e.g., intent, lethality, demographics, repetition, methods, prevalence, psychological consequences; Lofthouse et al., 2008).

Only two studies to date of which we are aware have examined neural correlates of reward-related processes in relation to NSSI. In the first study, adolescents with a history of suicidal and/or nonsuicidal self-harm, compared to those with no self-harm history, exhibited reduced activation in the striatum and orbitofrontal cortex (OFC) during reward anticipation (Sauder, Derbidge, & Beauchaine, 2016), suggesting blunted reward anticipation. However, it is unclear whether these reward anticipation findings generalize to other substages of reward responsiveness that are reflective of consummatory reward processing, other age groups, and to those who engage in self-injury without suicidal intent. The second study that examined the role of NSSI in relation to reward-related processes in a sample of women with BPD uncovered an overactivation of the OFC in response to unexpected reward during a gambling task in women with both BPD and NSSI, compared to women with BPD but without NSSI (Vega et al., 2017). Although suggestive of potential impaired reward valuation and/or poor behavioral control in individuals with co-occurring BPD and NSSI, it remains unclear whether these findings indicative of altered reward responsiveness in NSSI are observed transdiagnostically and in other age groups. Based on these gaps in the literature, what is needed to extend previous research are studies that examine reward responsiveness abnormalities in different age groups, across different levels of analysis, and in a way that allows for a fine-grained delineation of distinct subcomponents of reward responsiveness. To date, however, no studies have examined reward processing in children with a history of NSSI and no studies in any age group have examined neural correlates of consummatory reward processing among individuals with a history of NSSI transdiagnostically.

The primary aims of the present study were to address three key gaps in the literature. First, although NSSI constitutes a transdiagnostic behavior, most previous studies have focused on it within the context of a single disorder. Second, NSSI research is dominated by self-reported assessments of the correlates of this behavior. Third, virtually nothing is currently known about the correlates of NSSI in children. To address these limitations, we focused on the feedback negativity (FN) event-related potential (ERP) component in a transdiagnostic sample of children with and without a history of NSSI. The FN is thought to track quantitative reward prediction errors and is larger for the outcomes that are worse than expected (Holroyd & Coles, 2002; for a review, see Walsh & Anderson, 2012). It has been utilized by previous research as an objective psychophysiological quantifier of initial response to reward and appears to reflect a binary evaluation of outcomes as either favorable or unfavorable (Hajcak, Moser, Holroyd, & Simons, 2006). The FN is maximal at approximately 250–300 ms postfeedback over fronto-central recording sites and presents as a relative negativity in response to negative, compared to positive, outcomes (Gehring & Willoughby, 2002; Miltner, Braun, & Coles, 1997). Converging

empirical evidence from multimethod and cross-species designs suggests that the FN originates from the anterior cingulate cortex (ACC; e.g., Gehring & Willoughby, 2002; Hauser et al., 2014; Miltner et al., 1997; Smith et al., 2015; Warren, Hyman, Seamans, & Holroyd, 2015). Relatedly, neurobiological evidence suggests that individuals who engage in NSSI experience hyperarousal of limbic structures, including the ACC (Niedtfeld et al., 2010; Plener, Bubalo, Fladung, Ludolph, & Lule, 2012). Due to the substantial evidence in support of the link between the ACC functioning and reward processing (for a review, see Holroyd & Umemoto, 2016), an impaired ACC function in individuals with NSSI might be reflective of general reward responsiveness deficits, although the nature and direction of these deficits are currently unclear. A larger (i.e., more negative) FN is also correlated with increased behavioral and self-report measures of reward sensitivity (Bress & Hajcak, 2013). Numerous studies demonstrate that the FN can be elicited and assessed with a simple guessing task (e.g., Bress, Meyer, & Hajcak, 2015; Bress, Smith, Foti, Klein, & Hajcak, 2012; Foti, Weinberg, Dien, & Hajcak, 2011; Kujawa, Proudfit, & Klein, 2014; Nelson, Perlman, Klein, Kotov, & Hajcak, 2016; Tsypes, Owens, Hajcak, & Gibb, 2017; Weinberg, Liu, Hajcak, & Shankman, 2015). Indeed, this task has also been highlighted for the assessment of reward responsiveness by a recent NIMH report on behavioral assessment methods for RDoC constructs (National Advisory Mental Health Council Workgroup on Tasks and Measures for Research Domain Criteria, 2016). To date, however, no studies have examined the FN in relation to NSSI, despite its utility in objectively assessing neural correlates of initial responsiveness to reward in a cost-effective manner, which is well tolerated, even by children (Nelson & McCleery, 2008). Given the limited research in this area, coupled with the mixed findings with regard to the direction of reward responsiveness abnormalities (i.e., hypo- or hypersensitivity) in self-harming individuals, we did not make any specific hypotheses regarding the direction of the FN differences in this study.

Method

Participants and procedure

Participants for this study were drawn from a larger sample of children recruited from the community (via Facebook and television ads). To be eligible to participate in the larger study, children had to be between the ages of 7 and 11 and have no learning or developmental disorders that would make it difficult for them to complete the study. A total of 57 children were selected from the larger project (n = 955) for the purposes of the current study based on their history of NSSI. Using a 1:2 matching ratio, we included 19 children with a history of NSSI and a demographically matched sample of 38 children with no history of NSSI. As can be seen in Table 1, however, children in the NSSI group had significantly higher levels of externalizing problems and were also significantly more likely to have a history of major depressive disorder. The average age of the children in our study was 9.65 years (SD = 1.41) and 40.4% were female. In terms of race, 57.9% of the children were Caucasian, 22.8% were African American, 15.8% were Biracial, 1.8% were Native American/Alaskan, and 1.8% were Asian/Pacific Islander. In terms of ethnicity, 17.5% of the children were Hispanic. The demographic and clinical characteristics of the NSSI and no NSSI groups are presented in Table 1.

Upon arrival at the laboratory, parents were asked to provide informed consent and children were asked to provide assent to be in the study. Next, the child completed the reward task. During this time, the Schedule for Affective Disorders and Schizophrenia for School-Age Children – Present and Lifetime Version (K-SADS-PL; Kaufman et al., 1997) was administered to the parent by a trained interviewer. Following this, the same interviewer who had administered the K-SADS-PL to the parent also administered it to the child. The Institutional Review Board approved all procedures. Families were compensated a total of $90 for their participation. All children also received a bonus of $5 for completing the reward task.

Measures

Diagnoses and symptoms. The K-SADS-PL was used to assess for current and past DSM-IV MDD and anxiety disorders in children. In our matched sample, a total of five children (one girl, four boys) met criteria for a lifetime history of MDD and a total of eight children (four girls, four boys) met criteria for a lifetime history of an anxiety disorder. Specifically, five children met criteria for generalized anxiety disorder, five met criteria for separation anxiety disorder, one met criteria for post-traumatic stress disorder, and one met criteria for social anxiety disorder (Note: These numbers are >8 because of comorbidity). To assess inter-rater reliability, a subset of 20 diagnostic interviews from this project was coded by a second interviewer and kappa coefficients for diagnoses of MDD and anxiety disorders were good (all $\kappa \geq .86$). In addition to lifetime diagnoses, children's current symptoms of depression, anxiety, and externalizing problems were assessed using the Children's Depression Inventory (CDI; Kovacs, 1981), the Multidimensional Anxiety Scale for Children (MASC; March, Parker, Sullivan, Stallings, & Conners, 1997), and the Child Behavior Checklist (CBCL; Achenbach & Rescorla, 2000) Externalizing subscale, respectively. The internal consistencies of the CDI and MASC scales and the CBCL Externalizing subscale were 0.68, 0.89, and 0.91, respectively.

NSSI engagement. As part of the K-SADS-PL, interviewers assessed for children's history of NSSI by asking the following questions: "Did you ever try to hurt yourself? Have you ever burned yourself with matches/candles? Or scratched yourself with needles/a knife? Your nails? Or put hot pennies on your skin? Anything else?" Any affirmative responses were probed by further asking "Some kids do these types of things because they want to kill themselves, and other kids do them because it makes them feel a little better afterwards. Why do you do these things?" Only children who endorsed self-harm without an intent to kill themselves were included in the NSSI group. In our sample, the types of self-harming behaviors endorsed were cutting, punching, scratching, biting themselves or banging their head against things.

Reward task. The reward task was a simple guessing task (see Figure 1) that is commonly used in studies of reward processing (e.g., Bress et al., 2012, 2015; Foti et al., 2011; Kujawa et al., 2014; Nelson et al., 2016; Tsypes et al., 2017; Weinberg et al., 2015). The task consisted of 50 trials, presented in 2 blocks of 25 trials. Participants were shown an image of two doors at the beginning of each trial and instructed to guess by pressing either left or right button on a

Table 1 Descriptive statistics for children in each of the two groups

Measure	NSSI (n = 19)	No NSSI (n = 38)	$r_{\text{effect size}}$
Demographics			
Age	9.96 (1.49)	9.50 (1.36)	.16
Sex (% female)	36.8%	42.1%	−.05
Race (% Caucasian)	63.2%	55.3%	.08
Household Income (median)	20,001–25,000	20,001–25,000	−.01
Diagnoses			
Child lifetime MDD	4 (21.1%)	1 (2.6%)	.31*
Child lifetime anxiety dx	5 (26.3%)	3 (7.9%)	.25
Symptoms			
CDI	8.18 (5.71)	6.43 (3.55)	.19
MASC	47.75 (19.44)	48.97 (16.91)	−.03
CBCL Externalizing	14.22 (9.64)	5.93 (5.32)	.45**

MDD, Major Depressive Disorder; Dx, diagnosis; CDI, Children's Depression Inventory; MASC, Multidimensional Anxiety Scale for Children; CBCL, Child Behavior Checklist.
*p < .05, **p < .01.

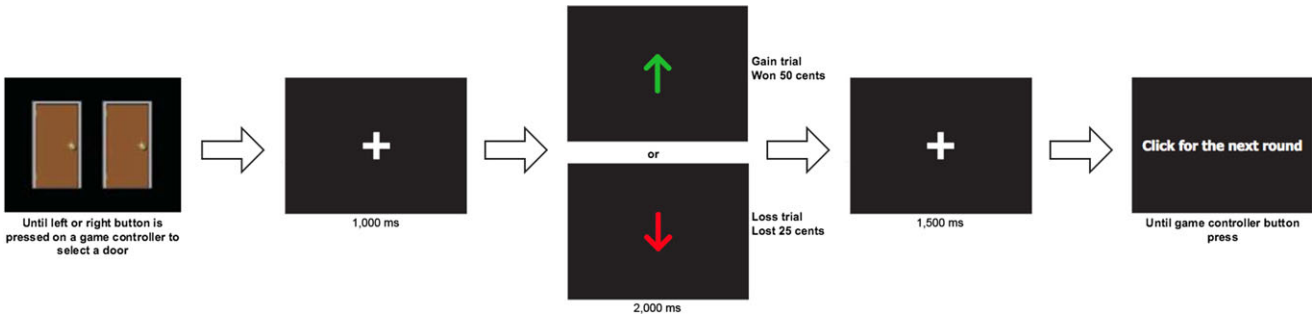

Figure 1 Trial structure of the reward task [Colour figure can be viewed at wileyonlinelibrary.com]

game controller which door had a monetary prize behind it. They were informed on each trial that they could either win $0.50, as indicated by a green up-arrow, or lose $0.25, as indicated by a red down-arrow. Feedback about having chosen correctly or incorrectly was presented for 2,000 ms, which was followed by the message 'Click for the next round'. This message remained on the screen until the participant responded and the next trial began. Across the task, 25 gain trials and 25 loss trials were presented in a random order.

EEG data acquisition and processing. During the task, continuous EEG was recorded using a custom cap and the BioSemi ActiveTwo system. The EEG was digitized at 24-bit resolution with a sampling rate of 512 Hz. Recordings were taken from 34 scalp electrodes based on the 10/20 system. The electrooculogram was recorded from four facial electrodes. Offline analysis was performed using the Matlab extension EEGLAB (Delorme & Makeig, 2004) and the EEGLAB plug-in ERPLAB (Lopez-Calderon & Luck, 2014). All data were rereferenced to the average of the left and right mastoid electrodes and band-pass filtered with cutoffs of 0.1 Hz and 30 Hz. EEG data were processed using both artifact rejection and correction. Large and stereotypical ocular components were identified and removed using independent component analysis (ICA) scalp maps (Jung et al., 2001). Epochs with large artifacts (>100 μV) were excluded from analysis. EEG was segmented for each trial, beginning 200 ms before onset of the feedback stimulus and ending 600 ms after onset of the feedback stimulus. For the NSSI group, the average number of gain trials remaining following artifact rejection was 22.05 (SD = 2.99, range = 16–25) and the average number of loss trails was 21.84 (SD = 2.63, range = 17–25). For the no NSSI group, the average number of gain trials remaining following artifact rejection was 22.89 (SD = 2.30, range = 16–25) and the average number of loss trails was 22.92 (SD = 2.34, range = 16–25). There was no significant between-group difference in the number of gain or loss trials accepted. ERPs were separately averaged across gain and loss trials, and the activity 200 ms before feedback onset served as the baseline. Consistent with previous research (e.g., Bress et al., 2012, 2015; Kujawa et al., 2014; Tsypes et al., 2017), the FN was scored as the mean amplitude 275–375 ms following feedback. To reduce noise associated with a recording at a single electrode, the FN was scored as the average activity across fronto-central electrode sites (i.e., Fz and FCz; cf. Bress et al., 2015; Tsypes et al., 2017). We examined the ΔFN calculated as difference in mean amplitude to loss trials minus gain trials as well as the mean amplitude on gain and loss trials separately.

Results

First, we conducted a 2 (group: NSSI, no NSSI) × 2 (condition: gain, loss) repeated measures ANOVA with children's FN amplitude serving as the dependent variable. Although the main effect of child NSSI group was not significant, $F(1, 55) = 0.02$, $p = .90$, $\eta_p^2 < .001$, there was a significant main effect of condition, $F(1, 55) = 29.22$ $p < .001$, $\eta_p^2 = .35$. Consistent with previous studies, across the full sample responses to losses ($M = 6.53$; $SD = 10.76$) were significantly less positive than responses to gains ($M = 11.88$; $SD = 10.10$), $t(56) = -5.34$; $p < .001$. There was also a significant group × condition interaction, $F(1, 55) = 6.24$, $p = .02$, $\eta_p^2 = .10$. Examining the form of this interaction, children with NSSI, $t(18)$

= −4.11; $p < .01$, and without NSSI, $t(37) = -2.80$; $p < .01$, had larger FN responses to losses than to gains; however, the NSSI group difference was not significant when examining responses to gains, $F(1, 55) = 1.32$, $p = .26$, $\eta_p^2 = .02$, or losses, $F(1, 55) = 0.72$, $p = .40$, $\eta_p^2 = .01$, separately.

Focusing then on the ΔFN, we conducted a one-way ANOVA with NSSI group (yes, no) serving as the independent variable and ΔFN magnitude serving as the dependent variable. We found a significant group difference in ΔFN, $F(1, 55) = 6.24$, $p = .02$, $\eta_p^2 = .10$, with children with a history of NSSI exhibiting significantly more negative ΔFN than children with no history of NSSI (see Figure 2). Follow-up analyses were then conducted to determine whether the group difference would be maintained after statistically controlling for the influence of a number of demographic and clinical variables. The group difference in ΔFN was maintained when we statistically controlled for the influence of children's current symptoms of depression, $F(1, 54) = 6.00$, $p = .02$, $\eta_p^2 = .10$, anxiety, $F(1, 54) = 6.46$, $p = .01$, $\eta_p^2 = .11$, or externalizing symptoms, $F(1, 54) = 5.80$, $p = .02$, $\eta_p^2 = .10$. Furthermore, it was maintained when we controlled for the influence of children's current symptoms of depression, anxiety, and externalizing symptoms simultaneously, $F(1, 52) = 4.13$, $p = .047$, $\eta_p^2 = .07$, suggesting that the results are not simply due to the presence of current internalizing or externalizing symptoms in children. The group difference in ΔFN was also maintained when we excluded children with a lifetime history of MDD or an anxiety disorder, $F(1, 45) = 6.12$, $p = .02$, $\eta_p^2 = .12$. Finally, the findings were maintained when the children of parents with a suicide attempt history were excluded from the analyses, $F(1, 47) = 5.28$, $p = .03$, $\eta_p^2 = .10$, suggesting that these effects are not simply driven by the intergenerational transmission of risk (cf. Tsypes et al., 2017).

Exploratory analyses were also conducted to examine the potential role of child age and sex. To this end, we first conducted a 2 (group: NSSI yes, NSSI no) × 2 (condition: gain, loss) × child age general linear model with children's FN amplitude serving as the dependent variable. There was a significant condition × age interaction, $F(1, 54) = 7.53$, $p < .01$, $\eta_p^2 = .12$. Follow-up analyses showed that there was a significant correlation between children's age and their FN amplitudes in the gain ($r = .29$, $p = .03$), but not in the loss condition ($r = -.03$, $p = .83$). We also conducted a 2 (group: NSSI yes, NSSI no) × 2 (condition: gain, loss) × 2 (sex: male, female) general linear model with children's FN amplitude serving as the dependent variable, but none of the interactions were significant (lowest $p = .83$).

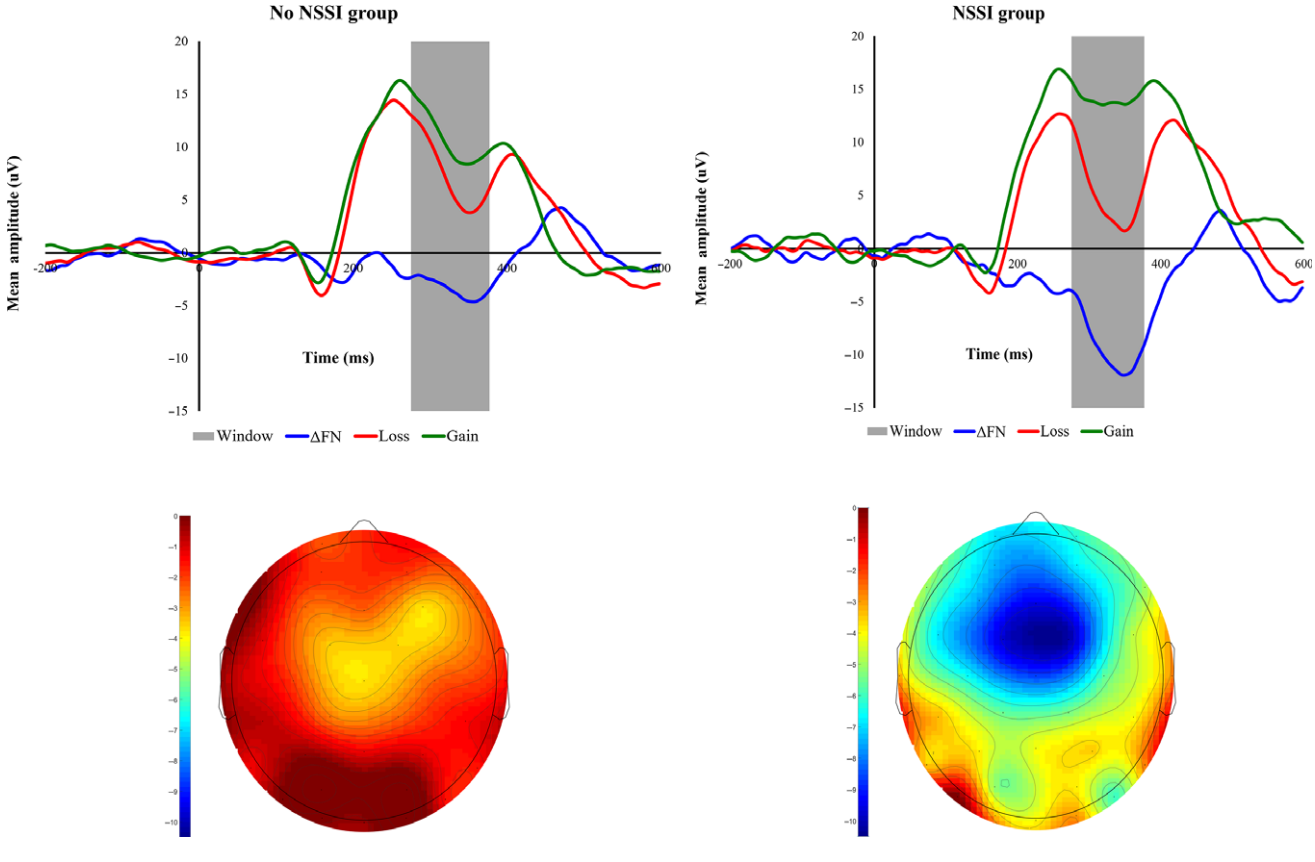

Figure 2 (Top) Stimulus-locked event-related potentials to feedback indicating monetary loss (red, middle) and gain (green, top), as well as the difference waveform (i.e., ΔFN) for loss minus gain trials (blue, bottom) for children with (right) and without (left) a history of NSSI. The gray region (window) shows the measurement window for FN (275-375 ms). Waveforms are averaged across Fz and FCz. (Bottom) Topographic scalp maps (in μ*V*) for the ΔFN ERP component 275–375 ms postfeedback for children with (right) and without (left) a history of NSSI. See the online article for the color version of this figure [Colour figure can be viewed at wileyonlinelibrary.com]

Discussion

The goal of this study was to examine initial response to reward in children with versus without a history of NSSI. We found that children with a history of NSSI exhibited significantly more negative ΔFN reflecting greater neural response to losses versus rewards than children with no history of NSSI. Importantly, these findings appeared to be at least partially independent of children's history of psychopathology and current internalizing and externalizing symptoms, suggesting their specificity to NSSI. Our results extend the currently scarce literature on reward responsiveness in individuals who engage in NSSI by providing first empirical evidence for heightened reactivity to losses versus rewards in children with NSSI. Given the link between the FN and ACC functioning (e.g., Gehring & Willoughby, 2002; Hauser et al., 2014; Miltner et al., 1997; Smith et al., 2015; Warren et al., 2015), these findings are consistent with the neurobiological evidence demonstrating impairments in the ACC functioning in individuals who engage in NSSI (e.g., Niedtfeld et al., 2010; Plener et al., 2012) and provide initial evidence that these disruptions might also manifest in the form of altered ΔFN in reward-related context. Interestingly, the pattern of these ΔFN findings is similar to what we observed in children of parents with a suicide attempt history (Tsypes et al., 2017), suggesting that more negative ΔFN, driven by a combination of larger response to loss and smaller response to gain, might represent a general marker associated with risk for self-harm. In this context, it is important to note that the current findings were maintained even when we excluded children of parents with a history of SA, suggesting that the current findings were not due simply to parents' history of SA.

The present study exhibited a number of strengths and constitutes an important addition to the literature on reward responsiveness in individuals who engage in NSSI. Specifically, it is the first study to examine initial reward responsiveness in children with NSSI at any level of analysis. In addition, it is the first study to transdiagnostically examine neural initial reward responsiveness abnormalities associated with engagement in NSSI in any age group. Additional strengths include the use of a demographically matched sample and the tests of robustness to rule out a number of other likely explanations for the FN differences. Importantly, the study may also help to clarify previous mixed findings with regard to the direction of reward responsiveness abnormalities in self-harming individuals. Specifically, although conclusions must remain tentative pending replication, our findings suggest that whereas self-harm might be linked with reduced neural activation in the reward processing-related brain regions during reward anticipation (Sauder et al., 2016), it might be the magnitude of neural differentiation in the loss versus gain trials that is more linked with the impairments in initial reward responsiveness. This is consistent with evidence that anticipatory (i.e., reward anticipation) and consummatory (i.e., initial response to reward and reward satiation) reward processing are distinct processes with separable neural correlates (e.g., Liu et al., 2011). These findings also complement those of a recent study focused on women with BPD, which suggests potential impaired reward valuation in individuals with co-occurring BPD and NSSI (Vega et al., 2017). Specifically, although future replications are needed, it is possible that children who engage in NSSI demonstrate heightened neural initial reward responsiveness to losses versus gains (i.e., higher reward sensitivity) due to impairments in reward valuation. According to a new comprehensive conceptual model of NSSI (The Benefits and Barriers Model of NSSI; Hooley & Franklin, 2018), one of the benefits of engagement in NSSI is its empirically supported ability to improve affect. Based on the present study's findings, it is possible that alterations in reward responsiveness/valuation in individuals with NSSI might lead them to overvalue short-term positive benefits of NSSI engagement (e.g., its ability to reliably improve affect), compared to longer term negative effects of this behavior. Because the affective benefits of NSSI might be more or less prominent for some individuals, it would be fruitful for future studies to examine the ways in which alterations in reward responsiveness might be implicated in the initiation and maintenance of NSSI. More broadly, our findings also highlight the importance of examining different subconstructs of reward responsiveness at a neural level of analysis, which can provide more fine-grained information about different subconstructs of reward responsiveness than can be obtained with self-reports.

Despite these strengths, the study also had some limitations, which provide important directions for future research. First, because of the cross-sectional design of our study, future research is needed to examine the temporal relation between the FN magnitude and NSSI engagement, specifically the predictive validity of the FN for future NSSI. Second, because the present study focused on the initial response to reward assessed via the FN, it will be important for future research to further separate neural activity elicited during different stages of reward processing in relation to self-harm. Third, because our study focused specifically on children with a history of NSSI, it will be important to examine whether the findings generalize to other self-harming thoughts and behaviors, such as suicidal ideation and suicide attempts in children. Relatedly, because of the relatively low base rates of NSSI in children, we were only able to examine its presence versus absence and future studies are needed to examine the potential impact of NSSI characteristics, such as its recency,

frequency, and severity, as potential moderators of the relation between the FN magnitude and NSSI. Fourth, because additional internalizing and externalizing disorders in children and in their parents (e.g., attention-deficit/hyperactivity disorder, bipolar disorder, substance dependence) might affect reward processing abnormalities in children, it will be important for future studies to examine their potential role in the link between NSSI and FN. It is important to note, however, that our findings were maintained when controlling for externalizing problems in children. Finally, although the size of our NSSI group was typical for an ERP study, it was still relatively small and thus it will be important for future studies to replicate our findings in larger samples.

In sum, the present study provides several important contributions to extant literature. Specifically, it provides initial evidence that children with a history of NSSI exhibit heightened neural reactivity to losses versus rewards, which is at least partially independent of their history of psychopathology or current symptoms. In addition to the contributions of these findings to the empirical literature on NSSI in children, they may also have clinical implications in suggesting that children with a history of NSSI exhibit abnormal neural responses to both gains and losses (less of a divergence in response to gains and losses compared to children with no history of NSSI). Due to the link between the ACC abnormalities and the reward responsiveness disruptions observed in the present study, our findings suggest that treatments aimed at normalizing the ACC functioning in children with NSSI might also improve their initial responsiveness to reward. Pending replications and extension of our results in longitudinal studies, these findings might have additional clinical implications by suggesting an early marker of reward responsiveness that could be used to identify, target, and prevent risk for self-harm. This is in line with the precision medicine movement in psychiatry, which is largely aimed at moving away from the one-size-fits-all approach to a more targeted treatment (Cuthbert, 2014; Williams, 2016). More specifically, in the future, the ΔFN might be used along with other neuroscience-based measures of risk in the patient-focused "Clinic of Tomorrow" (Siegle, 2011).

Acknowledgements

The project was supported by National Science Foundation Graduate Research Fellowship grant DGE1144464 awarded to AT and National Institute of Mental Health grant MH098060 awarded to BG. The authors thank Katie Burkhouse, Mary Woody, Anastacia Kudinova, Cope Feurer, Sydney Meadows, Michael Van Wie, Devra Alper, Eric Funk, Effua Sosoo, Nathan Hall, Kiera James, Aholibama Lopez, and Kristina Wong for their help in conducting assessments for this project. The authors have declared that they have no competing or potential conflicts of interest.

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Key points

- Improved understanding of the correlates of nonsuicidal self-injury (NSSI) in children is important for a better identification and prevention of current and future suicide risk.
- Although one potential transdiagnostic mechanism of risk for NSSI might be abnormalities in reward responsiveness, no studies to date have examined initial response to reward in individuals with a history of NSSI.
- The present study used the feedback negativity (FN) event-related potential, a well-established psychophysiological marker of initial responsiveness to reward, to address this gap in the literature.
- Children with a history of NSSI exhibited significantly more negative ΔFN (i.e., FN to losses minus FN to gains) than children without such history.
- Pending replications and longitudinal studies, ΔFN might constitute one of the psychophysiological markers of risk for self-harm.

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Accepted for publication: 1 March 2018
First published online: 17 April 2018