



RESEARCH ARTICLE

Neural sensitivity to social reward predicts links between social behavior and loneliness in youth during the COVID-19 pandemic

Sarah L. Dziura¹  | Kathryn A. McNaughton^{1,2}  | Elizabeth Giacobbe¹ |
 Heather A. Yarger¹  | Alexandra C. Hickey³  | Deena Shariq^{1,2}  |
 Elizabeth Redcay^{1,2} 

¹Department of Psychology, University of Maryland, College Park, Maryland, USA

²Neuroscience and Cognitive Science Program, University of Maryland, College Park, Maryland, USA

³Department of Communication Sciences and Disorders, University of South Carolina, Columbia, South Carolina, USA

Correspondence

Sarah L. Dziura and Elizabeth Redcay,
 Department of Psychology, University of Maryland, College Park, MD, USA.
 Email: sdziura@umd.edu and redcay@umd.edu

Funding information

National Institute of Mental Health,
 Grant/Award Numbers: R01MH125370,
 R01MH107441, R01MH112517

Abstract

Neural reward network sensitivity in youth is proposed to differentially impact the effects of social environments on social outcomes. The COVID-19 pandemic provided an opportunity to test this hypothesis within a context of diminished in-person social interaction. We examined whether neural sensitivity to interactive social reward moderates the relationship between a frequency of interactive or passive social activity and social satisfaction. Survey reports of frequency of interactions with friends, passive social media use, and loneliness and social satisfaction were gathered in 2020 during mandated precautions limiting in-person contact. A subset of participants (age = 10–17) previously participated in a functional magnetic resonance imaging (fMRI) study examining social-interactive reward during a simulated peer interaction (survey $n = 76$; survey + fMRI $n = 40$). We found evidence of differential response to social context, such that youth with higher neural reward sensitivity showed a negative association between a frequency of interactive connections with friends and a combined loneliness and social dissatisfaction component (LSDC) score, whereas those with lower sensitivity showed the opposite effect. Further, high reward sensitivity was associated with greater LSDC as passive social media use increased, whereas low reward sensitivity showed the opposite. This indicates that youth with greater sensitivity to social-interactive reward may be more susceptible to negative effects of infrequent contact than their low reward-sensitive counterparts, who instead maintain social well-being through passive viewing of social content. These differential outcomes could have implications for supporting youth during times of major social disruption as well as ensuring mental health and well-being more broadly.

KEYWORDS

adolescent, brain imaging, communication, emotion, social

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1 | INTRODUCTION

Middle childhood and adolescence are particularly sensitive developmental time periods, characterized by neurobiological changes as well as changes in social life and activity (Choudhury et al., 2006; Collins & Steinberg, 2006). Youth begin to rely less on caregivers and more on friends to meet their social needs (Larson & Richards, 1991), and these social changes are accompanied by increased attention to, and value placed on, social factors such as peer acceptance or alternatively, peer rejection (Sebastian et al., 2010). Significant changes in both structure and function of the brain support these changing social values (Blakemore & Mills, 2014; Kilford et al., 2016). Furthermore, there are increased risks for anxiety, depression, loneliness, and negative health outcomes if social needs are not met (Matthews et al., 2016; Roach, 2018). Some of these negative risk factors may have been exacerbated by the spread of COVID-19 and the resulting social isolation (Barendse et al., 2022; Orben et al., 2020; Yarger et al., *in press*). Examining associations between neural reward functioning in youth and their social behavior during the initial months of the pandemic can help determine best practices for supporting youth in critical developmental periods.

Anticipating and receiving reward feedback involves a domain-general network of brain regions, including parts of the ventral striatum (VS) (e.g., nucleus accumbens, ventral caudate, and ventral putamen), anterior cingulate cortex, and orbitofrontal cortex, as well as a number of secondary regions depending on contextual factors (Diekhof et al., 2012; Haber & Knutson, 2010; Liu et al., 2011; Murray, 2007). Social reward (e.g., smiling faces or praise) has been shown to involve this classic reward circuit as well as regions important for social and emotional processing such as the amygdala and medial prefrontal cortex (Izuma et al., 2008; Murray, 2007; Saxe & Haushofer, 2008; Zink et al., 2008). Prior studies using social-interactive rewards (i.e., youth believe that they are sending information to and receiving positive feedback from a peer in real time) demonstrate that greater activity to positive peer feedback relative to computer feedback and peer nonresponse control conditions is found in the VS and amygdala (Warnell et al., 2018). However, there is also variability in how people process and respond to social information, which may lead to very different experiences of social reward.

Variation in social motivation and reward processing is seen in both adolescent development and adulthood (Han et al., 2019; Kwon et al., 2019; Yacubian & Büchel, 2009). Such variability has been proposed to explain the differences in social behavior found in autism spectrum disorder, a condition characterized in part by social interaction challenges (Chevallier et al., 2012). Autistic youth are also at increased risk for negative social outcomes such as loneliness, potentially due to these social challenges (Deckers et al., 2017; Han et al., 2019). However, recent work suggests that neural activity in response to social-interactive reward is found in autistic youth to similar degrees as neurotypical (NT) youth, indicating transdiagnostic rather than group-level variability in social reward processing (McNaughton et al., 2023). These individual differences in reward processing that cut across autistic and NT populations may have downstream effects on behavior and

outcomes; for example, relative social reward activity in the VS in both autistic and NT youth is linked to an enjoyment of social experiences (McNaughton et al., 2023). Examining how social-interactive reward responses are linked to social behavior across diagnoses may serve to aid youth of all neurotypes who struggle with loneliness and other social difficulties.

Differential susceptibility theory suggests that the brain's variation in sensitivity to social reward (e.g., positive peer engagement) may not simply predict future social enjoyment but may also provide a marker of susceptibility to influence when youth are around peers. This increased susceptibility is then proposed to confer differential outcomes depending on the type of environment (Boyce, 2016; Do et al., 2020). In particular, those with greater reward response, and therefore greater susceptibility to peer influence, may experience beneficial outcomes in positive social environments but harmful outcomes in negative or risky social environments. Conversely, those with lower reward response may be resilient in the face of negative influence but may also be less likely to experience benefits when in positive environments. For example, people with high amygdala reactivity to facial expressions show a stronger relationship between socioeconomic resources and later income, a relationship that impacts those both at the positive (more resources = higher income) and negative (fewer resources = lower income) ends (Gard et al., 2018). Similar effects may also be found in a single direction, known either as diathesis–stress (on the negative end) or vantage sensitivity (on the positive end) (Pluess, 2015). For example, greater sensitivity in reward regions of the brain in response to social reward or punishment modulates adolescent risk taking and externalizing behavior in negative environments (Telzer et al., 2021; Turpyn et al., 2021), whereas some genetic markers have been shown to modulate primarily positive environments such as high maternal warmth (Richards et al., 2016). However, the link between reward susceptibility and social well-being within socially rich or impoverished environments has not yet been studied.

In early 2020, regulations put in place to combat the COVID-19 pandemic led to months of social distancing for youth, leading to a socially impoverished environment and adding further risk to an already risky time in life for poor mental health outcomes (Barendse et al., 2022; Loades et al., 2020; Qualter et al., 2010; Yarger et al., *in press*). As such, this window provided a unique opportunity to examine how variation in peer experiences may be related to social outcomes and whether individual differences in social reward sensitivity serves as an individual difference marker of differential susceptibility. Although on the surface, the pandemic may have caused some manner of general isolation from others (e.g., physical), some youth may be more disrupted by reduced in-person connection opportunities, whereas others may be able to maintain a rich social life through virtual means. Further, it is not clear how different types of social behavior may interact with such neural reward sensitivity in leading to these variable outcomes. Virtual social activity can range from simulated-realism with interactive visual and auditory social information being exchanged in real time (e.g., video calls) to pared-down but still temporally sensitive interactive information (e.g., texting or messaging) to fully passive (e.g., viewing images, videos, or messages without responding or

receiving responses). Work has shown that directly interacting with a social partner engages a broader network of brain regions compared to noninteractive social observation (Redcay & Schilbach, 2019). There may therefore be meaningful differences in reward and subsequent feelings of social satisfaction depending on the interactive level of the social activity that youth engage in.

In this study, we collected monthly data on social activity and social well-being after stay-at-home orders (SAHO) were first implemented from NT and autistic youth in the D.C. metropolitan area, both currently (i.e., over the last 2 weeks) and pre-SAHO (i.e., recalled behavior and feelings in a typical time before COVID, such as in February 2020). Forty of these participants had participated in a social-interactive reward functional magnetic resonance imaging (fMRI) task between 2015 and 2019. We hypothesized that relations between loneliness and social dissatisfaction component (LSDC) and directly interactive (i.e., frequency of connecting with friends) social behaviors post-SAHO would be moderated by neural sensitivity to social reward in the VS and amygdala. In particular, we expected that those with greater neural activity to social-interactive reward would show a steeper relationship between interactive connections with friends and LSDC, whereas those with lesser neural activity would show little or no relationship. Although we did not anticipate theoretical differences due to the mode of interaction (i.e., in-person or virtual connections), it was expected that in-person connections would be much lower overall post-SAHO. We also did not hypothesize specific differences due to the brain region of interest (ROI), as the previous work has shown that both regions respond similarly to social-interactive reward. However, we did expect that this differential sensitivity pattern may not be present for the relationship between passive social media use and LSDC, due to the noninteractive nature of this behavior.

2 | METHODS

2.1 | Participants

All youth included in the current study had previously participated in an MRI and/or behavioral session in our lab within the last 2 years and were at least 10 years old. Those who completed the surveys consisted of 76 youth (32 females) aged 10–17 (mean age = 13.84 years, $SD = 1.76$) and their parents. Fifty-eight participants were NT and 18 had a diagnosis of autism spectrum disorder (AUT). Forty participants (16 females) had prior useable fMRI data and were therefore included in the final sample (NT = 28, AUT = 12; mean age at MRI = 11.5 years, $SD = 1.69$; mean age at survey $T1 = 14.3$ years, $SD = 1.79$). In the final sample, 10% of participants identified as Black or African American, 62.5% identified as White, 22.5% identified as more than one race, and race was not reported for 2 participants (5%). Overall, 10% of participants identified as Hispanic or Latino, 85% identified as not Hispanic or Latino, and ethnicity was not reported for 2 participants (5%). Further demographic and session information is included in Table S1, Figures S1 and S2. Participants were recruited

from fliers, outreach events, and a database of local families interested in participating in research. Eligibility criteria for prior studies required that AUT participants have a clinical diagnosis of autism and meet research-diagnostic criteria based on the Autism Diagnostic Observation Schedule, Second Edition (ADOS-2). The ADOS-2 was conducted in a lab visit with a clinical psychologist (or clinical psychology Ph.D. student) who was research-reliable in administration and coding. To be included, both NT and AUT participants had to have a minimum IQ of 80, assessed using the Kaufman Brief Intelligence Test (KBIT-2; Kaufman & Kaufman, 2004). Results from prior work can be found in Warnell et al. (2018) and McNaughton et al. (2023). For the current follow-up study, parents who had previously consented to be recontacted were emailed with information about this study. Youth and their parents gave informed consent and assent prior to completing surveys in accordance with the Federal Policy for the Protection of Human Subjects and the Institutional Review Board at the University of Maryland, College Park.

2.2 | fMRI session

Youth completed a real-time peer interactive chat task developed by Warnell et al. (2018). Briefly, the task involved sending information about themselves and receiving positive responses from what was believed to be an age- and gender-matched peer or a computer, or else receiving away responses from either chat partner. Neural sensitivity to social-interactive reward was operationalized as the following contrast in Reply Periods (2 s): (Peer Agree–Peer Away)–(Computer Agree–Computer Away). The previous work in this lab has shown this task yields a greater average response to peer engagement relative to peer non-engaged and computer messages in the bilateral nucleus accumbens (VS) and amygdala (Warnell et al., 2018). More details are included in the Supporting Information section.

2.3 | COVID-19 survey collection

Youth and their parents participated in a follow-up study beginning in May 2020, shortly after SAHO were enacted due to the spread of COVID-19. This consisted of three sets of surveys sent on a monthly basis, including a youth response section and a parent response section. Additional demographics are detailed in Table S1. Surveys were sent to parents via email and completed via Qualtrics. Parents were sent the second and third round of surveys approximately 1 month after the completion of their previous survey. All data on social connections, loneliness, and social satisfaction were taken from youth report surveys. Youth completed the Adolescent Social Connection and Coping during COVID-19 Questionnaire (ASCC; Pfeifer et al., 2022). All post-SAHO measures asked participants to report how often they engaged in social behaviors “in the last 2 weeks.” Assessments of pre-SAHO social connections, loneliness, and social satisfaction were collected at each follow-up timepoint by asking participants to “think of a typical 2-week period before COVID-19 (e.g., in February).”

2.3.1 | Social-interactive connections

Social-interactive connections included both in-person and virtual connections as long as the interaction was reciprocal. Behaviors were reported on a scale of 1 (never) to 7 (almost constantly) both currently (in the last 2 weeks) and in a typical period before COVID-19 (e.g., in February). In-person interaction connection frequency was assessed by response to: "getting together with friends in person (outside of school or school-related activities)." Virtual interaction connection frequency was assessed by response to: "connecting with friends (from online or real life) without seeing them in person."

2.3.2 | Passive social media use

Passive social media use was defined as "scrolling through social media (e.g., pictures, stories, and TikTok) without posting, commenting, liking, or retweeting." This item was also collected on a scale of 1 (never) to 7 (almost constantly) both currently (in the last 2 weeks) and in a typical period before COVID-19 (e.g., in February).

2.3.3 | Loneliness and social dissatisfaction

A combined LSDC score was created from item-level responses on the NIH Toolbox Loneliness subscale of the Social Relationships Assessment and social needs met question from the ASCC. *Loneliness*: The NIH Toolbox Loneliness subscale (ages 8–17) is a seven-item measure on a scale from 1 (never) to 5 (always) and includes items such as "I feel left out" and "I feel alone and apart from others." *Social needs met*: This item (How well do you feel like your friends are meeting your social needs?) was reported on a scale of 1 (not at all) to 6 (extremely well) currently (in the last 2 weeks). Data examining responses to these measures separately are included in Supporting Information section.

2.4 | Data preparation

2.4.1 | Survey data

Forty participants returned one survey timepoint, 39 participants returned two survey timepoints, and 33 participants returned all three survey timepoints. Repeated measures ANOVAs were conducted to determine whether there were differences in either social behavior or feelings about social satisfaction reported across the three surveys. Additional multilevel model analyses were conducted to confirm that results were not due to missing data. The data did not differ across surveys within these subjects used in the fMRI interaction analyses, although in-person friend interactions and social media use did differ significantly across timepoints in the full survey sample ($N_{T1} = 76$, $N_{T2} = 70$, $N_{T3} = 54$). These results can be seen in Tables S2 and S3. As there were no differences across timepoints in the MRI sample, we averaged across all available surveys for further analysis. Correlations

between survey measures of interest averaged across all timepoints are displayed in Figure S3, and changes in measures from pre- to post-SAH0 are shown in Figure S4 and Table S4.

2.4.2 | Loneliness and social dissatisfaction component score

Due to the correlated nature of the two survey outcome measures of interest (social needs met by friends and loneliness; Figure S3) and because we did not have separate hypotheses about how the predictor variables would uniquely be associated with these outcomes, we conducted principal components analysis to determine whether a dimension reduction approach was appropriate for interaction model comparisons. Scaled responses from the seven items on the NIH Toolbox Loneliness subscale, and the single-item social needs met by friends question were entered into this analysis. The first component was shown to explain 64% of the variance in responses (Figure 1a) and was therefore selected as the sole outcome measure to use in further analysis. Figure 1b,c shows PC1's association with the two original variables; there is a strong positive relationship with loneliness and a negative relationship with social needs met. PC1 is subsequently referred to as "LSDC," with higher LSDC scores reflecting increased loneliness and reduced social needs met.

2.4.3 | fMRI data

VS (nucleus accumbens) and amygdala ROIs were chosen due to prior work examining social reward processing in autism (Clements et al., 2018) and results from social-interactive reward in both autism and typical development (Warnell et al., 2018; McNaughton et al., 2023). Average beta values from all four conditions were extracted from these regions, and the relative social-interactive reward response was calculated ([Peer Agree–Peer Away]–[Computer Agree–Computer Away]) for each bilateral ROI. This relative social-interactive reward contrast isolates both the effect of reward compared to no reward and the effect of a social compared to nonsocial stimulus. More details can be found in Supporting Information section.

2.5 | Data analysis

Separate linear regression models were conducted for LSDC with each interaction term between social behavior predictors of interest (in-person interactive connection frequency, virtual interactive connection frequency, passive social media use) and neural reward sensitivity in two ROIs (bilateral amygdala and bilateral VS) (i.e., six models total). Age at COVID survey T1, times between fMRI and survey dates of completion, sex, and diagnosis (AUT or NT) were included in each model as regressors of no interest. As there were only 12 AUT youth in the fMRI sample (full survey $n = 18$), we controlled for any potential group differences rather than directly test for them. A recent

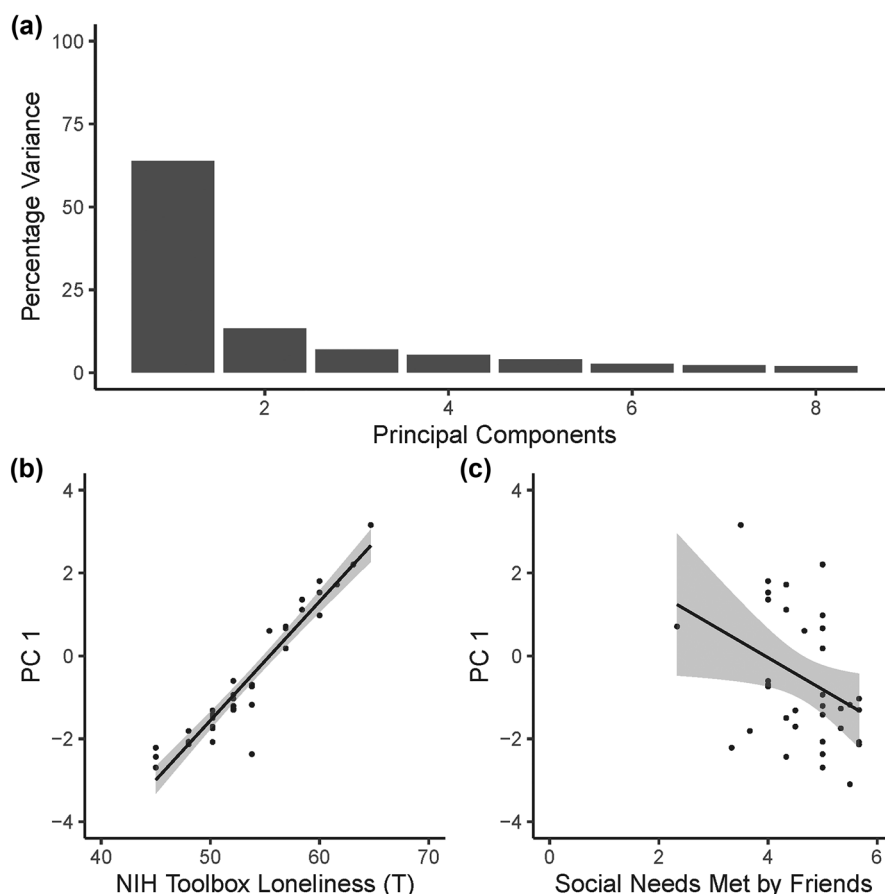


FIGURE 1 Principal components analysis (PCA) results for the two outcome measures (loneliness and social needs met by friends): (a) percent variance (64%) explained by PC1, (b) PC1 plotted against NIH Toolbox Loneliness subscale transformed to standard *T*-scores, (c) PC1 plotted against raw scores on the single-item response “How well do you feel like your friends are meeting your social needs?” PC1 is subsequently named “LSDC” (loneliness and social dissatisfaction component) throughout the text.

meta-analysis did not reveal group differences in social reward processing in the nucleus accumbens or amygdala between autistic and NT populations (Clements et al., 2018), and work with the same social-interactive reward paradigm in a larger sample did also not find group differences in social reward response in these ROIs (McNaughton et al., 2023), but future work with a larger and more balanced sample could directly examine differential sensitivity interactions with diagnosis. Preliminary comparisons can be seen in Table S5, Figures S5 and S6. Further, as pre- and post-SAHO reports of social activity were correlated (Figure S3), pre-SAHO reports of each relevant social activity were also included in each model as a regressor of no interest. Further analysis of specific pre-SAHO effects can be found in Supporting Information section. Predictors of interest were scaled prior to inclusion in the model, although unscaled predictors were used to visualize results (Figure 2). Holm-adjusted *p*-values were calculated and used for significance to correct for multiple model comparisons for each of the six models of interest. Bonferroni-corrected *p*-values were also calculated, and the more conservative correction did not change any results. All model results are displayed in Table S6.

Sensitivity analyses were conducted on models that produced significant behavior by neural sensitivity interactions. These included

determining the regions of significance (RoS) of the predictor variable (social activity) and simple slopes of the interaction variable (neural sensitivity) at ± 1 SD. These analyses were conducted using a web-based application developed by R. C. Fraley as a supplement to the recommendations of Roisman et al. (2012) (<https://www.yourpersonality.net/interaction/ros.pl>). The tests provide evidence to whether interactions are ordinal or disordinal, for example, whether they reflect theoretical patterns of differential susceptibility, whether they reflect only harmful (i.e., diathesis–stress) or only beneficial (i.e., vantage sensitivity) outcomes, or whether they reflect some other pattern of interaction between predictors.

3 | RESULTS

3.1 | Neural response to social reward in the VS predicts the association between virtual interactive connections and loneliness and social dissatisfaction

We found that social reward sensitivity in the VS significantly moderated the relationship between virtual interactive connection frequency

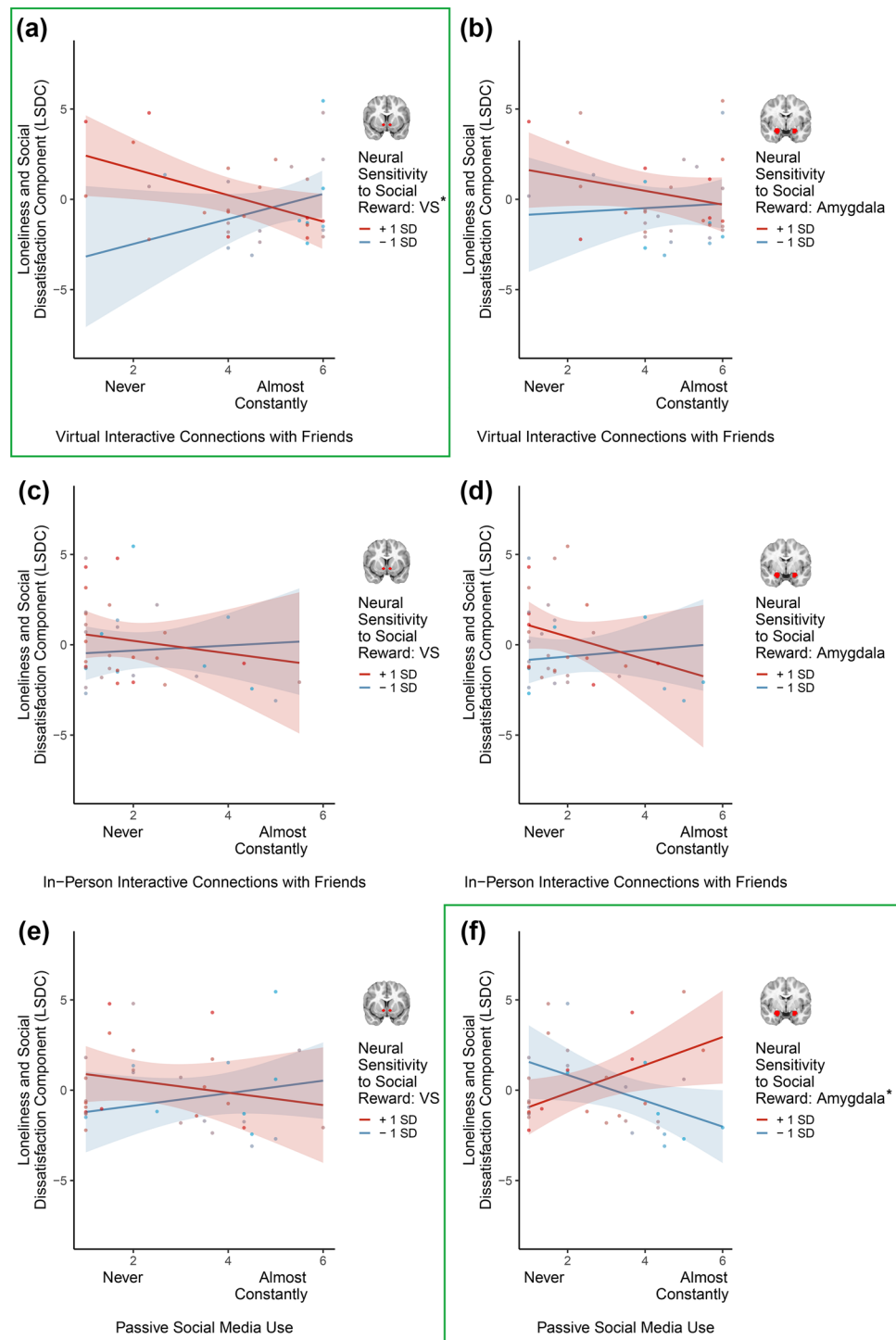


FIGURE 2 Relationship among different types of social activity and loneliness and social dissatisfaction component (LSDC), plotted as a function of neural social reward sensitivity (regression lines reflect ± 1 SD). Significant interactions are boxed in green: (a) virtual interactive connection frequency and ventral striatum (VS) sensitivity, (b) virtual interactive connection frequency and amygdala sensitivity (*n.s.*), (c) in-person interactive connection frequency and VS sensitivity (*n.s.*), (d) in-person interactive connection frequency and amygdala sensitivity (*n.s.*), (e) passive social media use and VS sensitivity (*n.s.*), (f) passive social media use and amygdala sensitivity.

with friends and LSDC ($B_{VS} = -1.08$, $p < .02$, corrected). This pattern showed a negative association between frequency of virtual connection and LSDC in high-reward-sensitive adolescents, but a positive relationship in low-reward-sensitive adolescents (Figure 2a). This interaction was not significant in the amygdala (Figure 2b). Follow-up simple slope analyses revealed that low VS sensitivity was significant in predicting LSDC (-1 SD: $B_{VS} = 1.32$, $p = .02$), and high VS sensitivity was marginally significant in predicting LSDC ($+1$ SD: $B_{VS} = -.82$, $p = .09$). Inspection of the RoS of virtual interactive connections revealed that only the low end of the x-axis (e.g., infrequent connections) significantly interacted with VS sensitivity to predict differences in LSDC (lower threshold = 3.64, 20% of values fall below; upper threshold = 6.34, 5% of values fall above). Together, this evidence suggests a one-sided diathesis-stress framework with potential negative outcomes for high-reward-sensitive youth, but a one-sided advantage sensitivity framework with potential positive outcomes for low-reward-sensitive youth. Unlike virtual interactive connections, no significant interactions were found with in-person friend connection frequency post-SAO (Figure 2c,d).

3.2 | Neural response to social reward in the amygdala predicts the association between passive social media use and loneliness and social dissatisfaction

We found that social reward sensitivity in the amygdala significantly moderated the relationship between the frequency of passive social media use (without direct interactions) and LSDC ($B_{amyg} = 1.15$, $p < .05$, corrected) (Figure 2f). This pattern was not found in the VS (Figure 2e). Follow-up simple slope analyses revealed that high amygdala sensitivity was significant in predicting LSDC ($+1$ SD: $B_{amyg} = 1.13$, $p = .02$), and low amygdala sensitivity was marginally significant in predicting LSDC (-1 SD: $B_{amyg} = -1.2$, $p = .07$). Inspection of the RoS of passive social media use yielded evidence that both ends of the x-axis (e.g., infrequent and frequent passive social media use) significantly interacted with amygdala sensitivity to predict differences in LSDC (lower threshold = 1.01, 25% of values fall below; upper threshold = 4.02, 30% of values fall above). Together, this evidence suggests a two-sided differential sensitivity framework with potential positive and negative outcomes for both low-reward and high-reward-sensitive youth.

4 | DISCUSSION

Here, we show preliminary evidence that neural sensitivity to social-interactive reward in middle childhood and early adolescence is a susceptibility marker of later associations between social behavior and loneliness and social dissatisfaction. Youth who show a greater neural response to positive peer engagement were found to be more sensitive to reductions in virtual social-interactive connections within socially isolated environments. We found evidence for a diathesis-stress framework (i.e., infrequent social contact conferring risk), as high

reward-sensitive youth feel lonelier as their virtual contact decreases, and they also feel lonelier as their passive use of social media increases, that is, without directly interacting with friends. This suggests that seeing the social lives of others without being able to participate could be particularly linked to negative outcomes in these adolescents. Conversely, youth who show lower neural responses to positive social-interactive peer engagement are more resilient to socially isolating environments, as they report feeling less lonely than their high reward-sensitive counterparts with infrequent social contact. These results are consistent with literature showing that loneliness and social isolation are separate constructs, and further, that objective measures of social isolation differ from subjective perceptions of social isolation (Cacioppo et al., 2009; Heinrich & Gullone, 2006; Levin & Stokes, 1986; Matthews et al., 2016; Pressman et al., 2005). We show here that these differences can be linked back to neural sensitivity, where social isolation from friends is associated with loneliness for some but not others.

We also found that adolescents with low neural reward sensitivity report lower levels of loneliness with more frequent passive use of social media. This could indicate that seeing the social lives of others, particularly without participation, may in fact be beneficial for them. These results are two-sided (i.e., both infrequent and frequent passive social media use yielded differences in LSDC depending on reward sensitivity), although they do not follow a traditional differential susceptibility theory pattern, where those with low neurobiological reactivity are invulnerable to changes in environments. In contrast, we see that low reward-sensitive youth are also susceptible to changes in social experience; however, they are impacted by passive or non-reciprocal experiences instead of interactive experiences. Critically, this reveals a potential difference between passive and active social experiences based upon neural reward sensitivity. A large body of work has pointed to differences in the human brain when engaging in third-person (i.e., social observation) or second-person (i.e., social interaction) cognitive processes (Fuchs & De Jaegher, 2009; Redcay & Schilbach, 2019; Schilbach et al., 2013). Our results indicate the importance of separating observation from interaction, as they not only index distinct cognitive processes but also reveal differences in real-world social outcomes. In short, adolescents who receive less reward from socially interactive experiences can still feel lonely, and they can possibly mitigate those feelings of loneliness through changes in noninteractive social behavior.

Results did differ some across brain regions. In particular, the VS moderated social-interactive behavior, which directly involves social feedback, whereas the amygdala moderated passive social media use. The nucleus accumbens is an important part of the classic domain-general reward circuit, engaged when anticipating and receiving feedback, assigning value, and determining context (Day & Carelli, 2007; Diekhof et al., 2012; Liu et al., 2011). On the other hand, the amygdala is not always included in the primary reward circuit, although it is often found to be active during reward paradigms. It is possible that the amygdala's role in social reward is more dependent on reward salience or value, as this region is engaged more when processing reward outcomes (Liu et al., 2011) and is involved in socio-emotional salience

processing more generally (Adolphs, 2010; Murray, 2007). Both interactive (involving direct feedback from peers) and passive (e.g., scrolling through social media) behavior may therefore yield differential neural activity and social satisfaction depending on how salient youth find these types of social stimuli.

Conventional wisdom assumes that increased social media use is associated with a number of mental health harms for youth, and there is some evidence to support this (Ivrie et al., 2020; Rutter et al., 2021). However, our results show that these are likely context-dependent, as well as dependent upon an individual's response to interactive rewarding feedback from peers. A recent meta-analysis revealed that social networking site use is weakly associated with higher levels of ill-being, but that there are also associations with well-being (Valkenburg et al., 2022). Our data did not examine feelings about social comparison or self-esteem which may be linked to higher negative outcomes such as rejection, anxiety, and depression; rather, we focused specifically on noninteractive scrolling through social media sites and apps to compare against interactive connections with friends. For individuals with low neural response to social reward, social media may act as a window to an outside world that reduces feelings of loneliness during times of physical isolation without the need to interact in real time, which may be effortful without rewarding benefits (Tamir & Hughes, 2018).

Overall, these results are consistent with literature linking greater neural reactivity in the subcortical reward network to behavior changes in different social environments (Richards et al., 2016; Telzer et al., 2021; Turpyn et al., 2021). However, there are several factors to consider that limit our confidence in the robustness of these patterns. First, our interpretations are still speculative as results show associations between behavior and feelings at a point in time, rather than a causal link between initial behavior and subsequent feelings. Second, although we targeted data collection in autistic youth samples due to increased risk for loneliness and social disconnection (Deckers et al., 2017), not enough data were collected to study these adolescents independently. The early months of the COVID-19 pandemic resulted in a great deal of stress and hardship that was compounded in families with autistic children through the sudden loss of services, which may have impacted the ability and willingness of these families to participate in volunteer studies. We elected to keep all available data rather than further limiting our focus to NT adolescents, as previously stated, autistic adolescents are at particular risk for loneliness and excluding them from studies investigating factors relating to loneliness is therefore inadvisable. Preliminary patterns (displayed in Figures S5 and S6) suggest that although autistic and NT youth may differ in self-reported frequency of social activity, they may not necessarily differ along lines of susceptibility to reduced social contact. More work is needed to confirm these findings. Third, we were limited in some ways by the timing of our data collection. We did not have pre-COVID survey data on social connections, as that survey was developed specifically to examine the effects of COVID-19 on adolescent behavior. Recall reports were averaged across all three surveys for a more stable measure and included in the models to attempt to control for pre-pandemic social

behavior, but it is possible that recall was affected by susceptibility to negative social outcomes such as loneliness. Future work should aim to collect data about current behavior over time to reduce any possibility of recall bias. Additionally, the fMRI data were collected over several years, with the result being that some participants had longer gaps between their neural sensitivity data and their survey data. Although we did control for both survey age and change in age between the fMRI and survey session, adolescence is a time of rapid change in both social and neural development, and such changes are difficult to track in this case. Further work with larger samples, particularly including more autistic adolescents, as well as more frequent data collection practices such as ecological momentary assessment can confirm these exploratory patterns.

Overall, our data have important implications for interventions designed to promote well-being and resilience among adolescents, particularly during times of social stress. Namely, they should consider individual differences in reward sensitivity. Subsequent research should aim to specifically test whether adolescents can reduce feelings of loneliness through differential active or passive behavior changes depending on their sensitivity to social reward. Adolescents who are particularly sensitive to social reward may benefit from seeking out more opportunities for direct social interaction and spending less time scrolling through social media without receiving positive responses. On the other hand, those who do not have strong neural reward responses to frequent social interactions may benefit from seeking out more opportunities for noninteractive social behaviors, as they may be better served through maintaining regular passive observation of social content.

ACKNOWLEDGMENTS

Research reported in this publication was supported by the National Institute of Mental Health under award numbers R01MH125370, R01MH107441, and R01MH112517. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. The authors would like to thank the youth and their families who participated in this research. We also thank Kayla Velnoskey, Sydney Maniscalco, Aiste Cechaviciute, Jacqueline Thomas, Eleonora Sadikova, Meredith Pecukonis, and the staff at the Maryland Neuroimaging Center for assistance with data collection; Junaid Merchant and Dustin Moraczewski for data preprocessing assistance; and Kate Warnell and Laura Kirby for their work with the social-interactive reward paradigm design.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest, financial or otherwise.

DATA AVAILABILITY STATEMENT

Data from consenting and assenting participants that support the findings of this study have been uploaded to the National Institute of Mental Health Data Archive (NDA) under collection #2394 and are available upon request at <https://nda.nih.gov>.

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ORCID

Sarah L. Dziura  <https://orcid.org/0000-0002-5072-4299>
 Kathryn A. McNaughton  <https://orcid.org/0000-0003-3668-876X>
 Heather A. Yarger  <https://orcid.org/0000-0001-8031-0700>
 Alexandra C. Hickey  <https://orcid.org/0000-0003-1171-487X>
 Deena Shariq  <https://orcid.org/0000-0002-5326-3037>
 Elizabeth Redcay  <https://orcid.org/0000-0002-1568-3102>

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How to cite this article: Dziura, S. L., McNaughton, K. A., Giacobbe, E., Yarger, H. A., Hickey, A. C., Shariq, D., & Redcay, E. (2023). Neural sensitivity to social reward predicts links between social behavior and loneliness in youth during the COVID-19 pandemic. *Developmental Psychobiology*, 65, e22413. <https://doi.org/10.1002/dev.22413>