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Blunted Feedback Processing During Risk-Taking in Adolescents with Features of Problematic Internet Use

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Abstract

While the conceptualization of problematic Internet use (PIU) as a ‘behavioral addiction’ resembling substance-use disorders is debated, the neurobiological underpinnings of PIU remain understudied. This study examined whether adolescents displaying features of PIU (at-risk PIU; ARPIU) are more impulsive and exhibit blunted responding in the neural mechanisms underlying feedback processing and outcome evaluation during risk-taking. Event-related potentials (ERPs) elicited by positive (i.e. reward) and negative (i.e. loss) feedback were recorded during performance on a modified version of the Balloon Analogue Risk Task (BART) among ARPIU ($n=39$) and non-ARPIU subjects ($n=27$). Compared to non-ARPIU, ARPIU adolescents displayed higher levels of urgency and lack of perseverance on the UPPS Impulsive Behavior Scale. Although no between-group difference in BART performance was observed, ERPs demonstrated overall decreased sensitivity to feedback in ARPIU compared to non-ARPIU adolescents, as indexed by blunted feedback-related negativity (FRN) and P300 amplitudes to both negative and positive feedback. The present study provides evidence for feedback processing during risk-taking

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Contributors

Authors Crowley, Mayes and Potenza designed the study and wrote the protocol. Author Crowley designed the ERP paradigm and supervised data collection. Author Yau analyzed the ERP data, performed the statistical analysis and wrote an initial draft of the manuscript. Authors Crowley, Mayes and Potenza guided the data analytic approach and wrote additional text and edited subsequent drafts of the manuscript. All authors contributed to and have approved the final manuscript.

Conflict of Interest

The authors report no conflicts of interest with respect to the content of this manuscript. Dr. Potenza has consulted for Lundbeck and Ironwood pharmaceuticals; has had financial interests in Somaxon pharmaceuticals; received research support from Mohegan Sun Casino, Psyadon pharmaceuticals, the National Center for Responsible Gambling, the National Institutes of Health (NIH), Veterans Administration; has participated in surveys, mailings, or telephone consultations related to drug addiction, impulse-control disorders, or other health topics; has consulted for gambling, legal and governmental entities on issues related to addictions or impulse-control disorders; has provided clinical care in the Connecticut Department of Mental Health and Addiction Services Problem Gambling Services Program; has performed grant reviews for the NIH and other agencies; has guest edited journal sections; has given academic lectures in grand rounds, Continuing Medical Education events, and other clinical or scientific venues; and has generated books or book chapters for publishers of mental health texts. Ms. Yau, Dr. Mayes, and Dr. Crowley declare no potential conflict of interest.

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as a neural correlate of ARPIU. Given recent concerns regarding the growing prevalence of PIU as a health concern, future work should examine the extent to which feedback processing may represent a risk factor for PIU, a consequence of PIU, or possibly both.

Keywords

Problematic Internet Use; Feedback-Related Negativity; P300; Feedback Processing

1. Introduction

As of 2014, a staggering 97% of adolescents in the U.S. reported at least occasional Internet use (Pew Research, 2014). While most Internet users have no disruption in psychosocial functioning, a subset may exhibit problematic internet use (PIU) or 'Internet addiction'. This behavioral profile shares neuropsychological (e.g., development of craving, tolerance, and withdrawal) and personality characteristics (e.g., high risk-taking, low self-esteem) with substance-use disorders (SUDs) and has been considered a 'behavioral addiction' with criteria often mirroring those for SUDs (Ko et al., 2012).

Several lines of work implicate impaired feedback processing in the development and maintenance of addictive behaviors. Diminished error-related anterior cingulate cortex (ACC) activity – an area considered important in exerting adaptive and responsive behavioral control – has been identified among individuals with substance abuse (Garavan & Stout, 2005) and behavioral addictions (de Ruiter et al., 2012; Littel et al., 2012). Poorer ability to use feedback to guide ongoing behaviors may be associated with impulsive behaviors biased towards anticipated reward and decreased responsiveness to punishment (Garavan & Stout, 2005). We speculate that the same patterns may manifest in PIU subjects. Preliminary findings suggest increased impulsivity (see Armstrong, Phillips, & Sailing, 2000 for negative finding; Meerkerk et al., 2010; Yau, Potenza, & White, 2012) among individuals with features of PIU. Structural differences have also been observed; adolescent with PIU demonstrate lower gray matter density (Zhou et al., 2011) and abnormal white matter integrity (Lin et al., 2012) in the ACC. However, no work has directly examined feedback processing and reward valence in the context of PIU.

Event-related potentials (ERPs) hold promise for understanding mechanisms underlying feedback evaluation, particularly during risky decision-making. Two ERP components sensitive to feedback are the feedback-related negativity (FRN) (Fukunaga, Brown, & Bogg, 2012) and P300 (Nieuwenhuis et al., 2005). Localized to the ACC, the FRN peaks ~200–300 ms post-feedback (Fukunaga et al., 2012). The FRN is thought to reflect a neural response for outcomes worse than expected (Bellebaum, Poleszi, & Daum, 2010; Holroyd & Coles, 2002; Nieuwenhuis et al., 2005). Reinforcement learning theory posits that FRN is generated by dips in midbrain dopamine levels that signal disinhibitory neurons in the ACC (Holroyd & Coles, 2002). Acting as a motor-control filter, the ACC uses the reinforcement signals to determine the most suitable behavior for the task at hand (Holroyd & Coles, 2002). Importantly, FRN responses reflect activity in a system central to adaptive decision-making and subsequent behavior.

In contrast, the P300 component is a positive deflection peaking ~300–450ms post-feedback that reflects a later, attention-sensitive, more elaborate appraisal of outcome sensitivity to the reward magnitude (Hajcak et al., 2005; Sato et al., 2005; Yeung & Sanfey, 2004). The P300 amplitude is associated with processes of attention allocation and reflects the functional and motivational significance of feedback stimuli (Kleih et al., 2010). Although arguments were forwarded that the P300 is only sensitive to feedback valence, recent studies find that the P300 also encodes the evaluation reward magnitude (Hajcak et al., 2005; Leng & Zhou, 2010). Similar to the FRN, the P300 is thought to be generated by the ACC as well as other regions involved in the circuit between frontal and temporal-parietal areas (Nieuwenhuis et al., 2005).

ERPs have been examined concurrently with the Balloon Analogue Risk Task (BART) (Fein & Chang, 2008a), with task performance relating to behavioral risk-taking (Lejuez et al., 2002). In the BART, participants earn points based on the number of pumps selected to inflate a balloon. Greater numbers of pumps generate higher earnings, but also increase the risk that the balloon will burst, with no money earned for exploded balloons. Reductions in FRN and P300 response have been observed during negative events (i.e., popped balloons) among individuals with (Franken et al., 2007) or at-risk of developing SUDs (Crowley et al., 2009; Euser et al., 2013; Fein & Chang, 2008a). These findings support the notion that individuals engaged in addictive behaviors display abnormal feedback processing.

Adolescents may be particularly susceptible to addictive behaviors (Steinberg, 2008). This heightened vulnerability in adolescence may be due to the earlier maturation of regions involved in promoting reward-seeking behaviors compared to the maturation of region, such as the ACC, that comprise the “cognitive control system” involved in more advanced self-regulation and impulse control (Steinberg, 2010). Identifying vulnerability markers for PIU is a first step for developing effective treatment and prevention programs and may be particularly important for adolescents. The present study examined personality, behavioral, and biological components of the feedback monitoring system among adolescents stratified by the presence (i.e., at-risk problematic Internet use [ARPIU]) or absence of PIU features. Given the findings summarized above, we hypothesized that individuals with ARPIU, compared to those without, would (1) score higher on impulsivity scales, (2) display more risky behaviors during the BART, and (3) display hyposensitivity to negative feedback as elicited by blunted FRN and P300 responses.

2. Materials and Methods

2.1. Participants

Seventy-three adolescents were recruited from participants in an on-going normative, community-based sample referred to as the “stress-reward study” (Crowley, van Noordt, et al., 2013; Crowley, Wu, et al., 2013). Per parent report, participants had no evidence of serious mental illness (e.g. psychosis, autism, bipolar disorder) or medical conditions (e.g. tumor, neurological disorders, or epilepsy). After excluding seven participants whose data were not usable due to data artifacts in their EEG recording, a total of 36 females and 30 males were considered for analysis. Among the final sample ($N=66$), the mean age of the adolescents was 14.67 years ($SD=2.07$, range=10–19 years) and consisted of 16.7% African-

American, 69.7% Caucasian, 3.0% Asian, and 10.6% Other. Participants received 40USD for their participation.

2.2. Measures

At-Risk/Problematic Internet Use—As previously (Liu et al., 2011; Yau et al., 2012), adolescents were asked to report the number of hours spent using the Internet in a typical week. If adolescents acknowledged using the Internet, six additional questions were asked: (1) Do you think you have a problem with excessive Internet use? (2) Have you ever experienced an irresistible urge or uncontrollable need to use the Internet? (3) Have you ever experienced a growing tension or anxiety that can only be relieved by using the Internet? (4) Have you ever missed school, work, or an important social activity because you were using the Internet? (5) Have you ever tried to cut back on your Internet use? (6) Has a family member ever expressed concern about the amount of time you use the Internet? These questions were modeled after the Minnesota Impulsive Disorder Interview (MIDI) – a valid and reliable instrument used to screen for impulse-control disorders (Grant et al., 2005). Given the absence of a formal diagnostic criteria for PIU, a liberal threshold was employed with individuals classified as “at-risk” if they acknowledged one or more features of PIU (mean=2.09, SD=1.25) (see Table S1 and S2 for ARPIU group break). Those who either self-reported no Internet use in a typical week or endorsed none of the six questions were classified as non-ARPIU.

UPPS Impulsive Behavior Scale (UPPS)—The 45-item UPPS (Whiteside & Lynam, 2001) was used to evaluate impulsivity across dimensions of the Five Factor Model of personality. It covers four subscales: (lack of) Premeditation, Urgency, Sensation-Seeking, and (lack of) Perseverance (Whiteside et al., 2005) (see Supplementary Information for details). Though primarily designed for adults, this four-dimensional model has been replicated in adolescent samples (e.g. d’Acremont & Van der Linden, 2005) and has good internal reliability and validity (Whiteside et al., 2005).

Balloon Analogue Risk Task—An automatic response version of the BART with 60 trials was implemented with E-prime v2.0 (Psychology Software Tools, Inc.). Each trial displayed a balloon in the middle of the screen connected to a pump with a number dial below. The Cronbach α coefficient for the present study ranged from .71 to .82, suggesting good internal reliability for the various subscales. Only one balloon was presented per trial, each having a maximum breaking point of 128 pumps. Rather than sequentially pumping the balloon (as in the standard BART; (Lejuez et al., 2002)) - which arguably may not be an accurate measure of the impulsive processes underlying risk-taking behavior as it gives the individual time to reflect upon their decision - participants selected the target number of pumps (corresponding to how much risk) at the beginning of each trial. For each pump, participants could obtain one point; however, if the balloon popped, the accrued points for the trial would be lost (for task details see Supplementary Information). Participants were instructed to try to win as many points as possible.

In weighing the decision to provide sufficient numbers of popped balloons to provide for FRN responses against the fidelity of original BART, a 2-block hybrid task was adopted.

The first block of 30 balloons followed the “pop” points of the original BART (Lejuez et al., 2002) with balloon explosion probabilities following a normal distribution spread. The probability of the second block of 30 balloons popping was rigged such that there was a 50% chance of reward and 50% chance of loss across the task as long as the number of pumps was not extremely low (below 10) or extremely high (above 118). This ensured that a sufficient amount of “losing” trials (over 15 trials) would incur to allow for FRN recordings, while preserving the behavioral task, visually comparable to the original BART in the first 30 trials.

2.3. Procedures

After obtaining parental permission and child assent, participants completed the aforementioned questionnaires. Thereafter, all participants took part in the EEG/BART sessions, lasting approximately 90 minutes in total. A Hydrocel high-density array of 128 Ag/AgCl electrodes was applied following standard procedures with recording at 40 k Ω at the outset of the assessment (Geodesic Sensory Net, EGI Inc., Eugene, OR). After the EEG net was applied, the BART was administered via computer to measure feedback processing during risky-decision-making. Participants were given 2 practice trials to familiarize themselves with the BART. After completion of the BART, participants were fully debriefed. This procedure was approved by the Yale School of Medicine institutional review board.

2.4. EEG Processing

EEG data were recorded and processed using NetStation v4.4 software package (EGI, Inc.) and EGI high-impedance amplifiers, sampling at 250Hz (EGI, Inc., Series 300 amplifier) with online filters set at 0.1–100Hz. All electrode recordings were referenced to the Cz electrode which were then re-referenced offline for data analysis.

Data were filtered offline at 0.1–30Hz and segmented into epochs that covered a time-frame of 100ms pre-stimulus baseline and 600ms post-stimulus interval for analysis. Bad eye channels were manually marked and interpolated by surrounding channels. Epochs with any eye-blink or eye-movement (threshold 150 μ V) or containing more than 10 bad channels were rejected. The remaining bad segments were replaced by surrounding channels. Single-trial EEG data were re-referenced from the Cz electrode to an average reference as the latter better represents a true zero (Junghöfer et al., 1999). The baseline was corrected to 100ms pre-stimulus. ERPs were obtained by averaging the single trial data for the two blocks of the BART (normal and rigged). Only subjects with at least 10 artifact-free trials were included ($n=40$). Ocular artifact removal (OAR) was used for those that did not meet this threshold (Gratton, Coles, & Donchin, 1983). Participants who yielded at least 10 good trials with this additional approach ($n=26$) were included in the overall statistical analysis ($N=66$).

ERPs were computed by analyzing the mean amplitude in a time window post-onset of feedback for loss and reward trials respectively (Yeung & Sanfey, 2004). FRN amplitude was defined as the mean ± 25 ms from the negative peak amplitude between 200–300ms within an electrode cluster over the midline of the medial frontal region (channel numbers: 11 (Fz), 12, 5, and 6). The P300 component was defined as the mean ± 25 ms from the

positive peak amplitude between 300–450ms within an electrode cluster over the posterior region (channel numbers: 62, 67, 72, and 77) following the FRN peak.

2.5. Statistical Analysis

For all statistical analyses, an alpha level of .05 was employed. The associations between ARPIU and gender and ethnicity were analyzed by Chi-square tests. Between-group differences for age distribution and UPPS scores were examined using independent t-tests.

As in previous research using the automatic response version of the BART (Pleskac et al., 2008), the mean number of pumps across balloons during the BART was analyzed for the behavioral measure of risk-taking and served as the primary dependent variable.

Additionally, the deliberation time (i.e. the amount of time to decide on the number of pumps made) was examined. These measures were examined with a 2x2 repeated-measure ANOVA with group (ARPIU vs. non-ARPIU) as the between-subject factor and BART version (normal vs. rigged) as the within-subject factor.

For FRN and P300 amplitudes, 2x2 repeated-measure ANOVAs were performed with group (ARPIU vs. non-ARPIU) as the between-subject factor and feedback (reward vs. loss) as the within-subject factor. Greenhouse-Geisser correction was adopted for all F-tests reported (Greenhouse & Geisser, 1959). Bivariate correlation analyses using Pearson's correlation coefficient were used to examine associations between the various measures in both groups.

3. Results

Sample demographics are outlined in Table S3. The distribution of ethnicity (χ^2 (3, N=66)=0.176, $p=.98$), gender (χ^2 (1, N=66)=1.88, $p=.17$), and age (t (64)=−0.12, $p=.16$) were comparable between ARPIU and non-ARPIU groups. For descriptive purposes, associations between major study variables are presented in the supplementary materials (see Table S5).

3.1. UPPS Results

Table S4 presents the means and significant between-group differences on the UPPS. Main effects of Urgency (t (64)= −2.40, $p=.02$) and lack of Perseverance (t (64)= −2.19, $p=.03$) were found with scores higher among the ARPIU group compared to the non-ARPIU group on both subscales, suggesting they possessed poorer ability to resist cravings and poorer perseverance. No between-group differences for either lack of Premeditation (t (64)=0.01, $p=.99$) or Sensation-Seeking (t (64)=1.10, $p=.28$) scores were found.

3.2. BART Results

When stratifying the task into the two versions of BART implemented, repeated-measure ANOVAs indicated that task version had no main effect in regards to mean number of pumps (F (1, 62)=0.66, $p=.42$) or deliberation time (F (1, 62)=0.16, $p=.69$). Similarly, no BART-version-by-group interaction-effect was observed for the mean number of pumps (F (1, 62)=0.17, $p=.68$) or deliberation time (F (1, 62)=0.15, $p=.70$). Taken together, analyses suggest that the BART version did not influence the results.

Regarding the primary measure of risk-taking, no significant main effect of the mean target number of pumps (ARPIU: mean=54.42, SD=13.83; non-ARPIU: mean=54.96, SD=17.59) was observed ($F(1, 62)=0.28, p=.60$). Deliberation time (ARPIU: mean=3844.82ms, SD=1.23; non-ARPIU: mean=4009.17ms, SD=1.47) similarly failed to reach statistical significance ($F(1, 62)=0.15, p=.70$). Collectively, these results suggest that performance on the BART was not associated with ARPIU.

3.3. Electrophysiological Results

Repeated-measure ANOVAs conducted on the peak FRN amplitude (Figure 1) revealed a significant main effect of feedback ($F(1, 64)=9.63, p=.003$) indicating that the loss condition (mean=-0.81, SD=3.58) induced a larger negative deflection in the FRN response than the reward condition (mean=0.29, SD=2.69) (see Figure 2 for topographical distribution of current source density). Importantly, a significant between-group effect was found ($F(1, 64)=4.92, p=.03$), indicating that ARPIU adolescents (loss: mean=0.42, SD=3.46; reward: mean=0.64, SD=2.58) had an overall smaller FRN feedback compared to non-ARPIU controls (loss: mean=-2.05, SD=3.45; reward: mean=-0.23, SD=2.80), irrespective of feedback valence. No feedback-by-group interaction-effect was observed ($F(1, 64)=2.43, p=.12$).

Similar to the FRN, repeated-measure ANOVAs conducted on the peak P300 amplitude (Figure 3) revealed a significant main effect of feedback ($F(1, 64)=5.30, p=.03$) with the loss condition (mean=4.69, SD=4.60) eliciting larger positive peaks than the reward condition (mean=3.77, SD=4.17) (see Figure 4 for topographical distribution of current-source density). A significant between-group effect was observed ($F(1, 64)=4.76, p=.03$), indicating that in response to both types of feedback, ARPIU adolescents (loss: mean=3.62, SD=5.03; reward: mean=3.09, SD=4.70) displayed overall smaller P300 amplitudes than non-ARPIU controls (loss: mean=6.23, SD=3.43; reward: mean=4.76, SD=3.10). No feedback-by-group interaction-effect was observed ($F(1, 64)=1.14, p=.29$).

4. Discussion

To our knowledge, the present study is the first investigating relationships between ARPIU and the neural mechanisms underlying feedback processing and reward-prediction errors during risk-taking. As with previous studies (e.g., Billieux et al., 2010), ARPIU adolescents displayed higher self-reported levels of urgency and lack of perseverance compared to non-ARPIU adolescents; however, no between-group difference in behavioral risk-taking on the BART was observed. Importantly, ARPIU adolescents compared to non-ARPIU adolescents displayed blunted FRN and P300 response to both negative and positive outcomes, indicating overall decreased sensitivity to feedback.

We observed that amplitudes for both the FRN and P300 components in the fronto-central region were modulated by the valence of the outcome, with negative feedback inducing larger responses than positive feedback. The FRN appears to be predictive of ongoing shifts in decision-making (Yeung & Sanfey, 2004) and indexes violations of expected outcomes (Bellebaum et al., 2010). Consistent with findings in SUDs (Fein & Chang, 2008b), blunted FRN amplitudes were observed in ARPIU compared to non-ARPIU adolescents and may

reflect impaired ACC functionality (Holroyd & Coles, 2002), reduced emotional responding to errors (Bates et al., 2002), and elevated impulsivity (Ruchsow et al., 2005). According to reinforcement learning models (Holroyd & Coles, 2002), differences between anticipated and obtained reinforcements, or ‘prediction errors’, can guide decision-making by modulating the strength of weights for competing decision options. Given the role of prediction errors in adjusting future behavior (Ridderinkhof et al., 2004), attenuated FRN among ARPIU adolescents may indicate a diminished ability to use previous reinforcements to guide decision-making, potentially resulting in prolonged engagement in rewarding but risky behaviors. In addition, blunted P300 amplitudes among individuals with ARPIU suggest that the ability to subsequently assign sufficient attention to motivationally salient events may be impaired. As with SUDs (Hesselbrock et al., 2001; Porjesz et al., 1998), our findings suggest that the more elaborative and higher-order processes which contribute to the allocation of attention resource and cognitive endeavors are related to ARPIU.

Among both groups, significant correlations between P300 and FRN responses to loss conditions were observed, indicating that individuals demonstrating greater FRN amplitudes were also more likely to display greater P300 amplitudes. Furthermore, P300 and FRN responses to reward conditions were significantly correlated among individuals with ARPIU. These correlations suggest that individual differences in the neural correlates of outcome evaluation during risk-taking are related in early stages, as reflected by the FRN, and later stages, as reflected by the P300, particularly amongst individuals with ARPIU. Source localization analysis indicate that these two ERPs have overlapping source generators in the ACC (Nieuwenhuis et al., 2005), suggesting that ACC function may underlie these processes, although further studies are needed to address this issue.

Our analyses revealed that certain dimensions of self-reported impulsivity, namely urgency and lack of perseverance, appear related to ARPIU. Associated with the occurrence of a wide range of substance (Verdejo-Garcia, Lawrence, & Clark, 2008) and behavioral addictions (Smith et al., 2007), the construct of urgency may indicate an individual’s proneness to engage in maladaptive behaviors to regulate or relieve negative emotional experience (Selby, Anestis, & Joiner, 2008). Moreover, high-urgency individuals have demonstrated difficulties in making choices based on their future consequences during decision-making tasks (Dolan, Bechara, & Nathan, 2008). Urgency motivated risky and impulsive behaviors overlaps with concepts of addiction that suggest chronic substance use may further decrease inhibitory control (Robinson & Berridge, 2003).

Lack of perseverance has been hypothesized to map onto separate inhibitory functions from other facets of risk-taking such as urgency (Friedman & Miyake, 2004). Adolescents who lack perseverance typically display poorer ability to tolerate boredom, resist distracting stimuli and complete tasks (Whiteside & Lynam, 2001). Unlike impulsivity-related constructs such as sensation-seeking which may relate to initiation, both urgency and lack of perseverance relate to problems with disengaging from prolonged participation in risky behaviors (Verdejo-Garcia et al., 2008). This formulation is consistent with perspectives proposing that addiction follows an allostatic cycle from reward-seeking behavior to avoidance of negative states and compulsion (Everitt & Robbins, 2005). The Internet may represent a frequently changing, novel and psychologically rewarding environment that can

be anonymously and abundantly experienced at little to no cost. High-urgency individuals may have difficulty in refraining from accessing rapidly achievable and instantly rewarding stimuli that may help relieve negative affect in the short term. Similarly, individuals with low levels of perseverance may be motivated to continue Internet use to maintain (or resist extinction of) access to rewarding sources that may be unpredictable and difficult to achieve in the real world.

The absence of relationship between sensation-seeking with ARPIU is not in keeping with the pre-existing work on SUDs (Adams et al., 2012; Leeman et al., 2014). While Internet use may be stimulating, unlike substances, it does not possess psychotropic, hallucinatory, or anaesthetizing properties and may therefore not appeal to high sensation-seeking individuals. Moreover, previous studies indicate that adolescents with PIU typically score high on harm-avoidant assessments – a finding that also contrasts what is typically reported in the SUD literature and may in part explain the findings in the present study (Eckhoff, 2013; Ko et al., 2006). Although PIU and SUDs share much overlap, intervention strategies should consider these potential differences. Interestingly, no correlations were observed between the ERPs, self-reported personality traits or behavioral measures (i.e., BART performance). An explanation may be that each of these measures may differ in sensitivity and relate to different aspects of neuropsychological functioning. Further research investigating the relationships between these measures in the context of PIU is needed.

Several limitations merit consideration when interpreting our results. First, this study is correlational and cannot establish causal relationships. Longitudinal studies indicate that vulnerability markers may both pre-exist and worsen after one becomes a problematic user (van Rooij et al., 2010). Further work is needed to investigate a role for risk-taking and deficient feedback processing mechanisms at the onset and later stages of PIU, particularly with consideration of developmental epochs. Second, the self-report methodology employed to determine PIU is subject to biases that may lead to inaccurate reporting. It is possible that a “badge-of-honor” effect may motivate adolescents to exaggerate Internet use as a sign of a serious or experienced user. Alternatively, individuals may downplay the extent to which Internet use impacts their health and well-being. Third, although a strength of our study lies in the use of criteria based on symptoms/features of PIU rather than on the basis of frequency of use, the current lack of formal diagnostic criteria for PIU limits the study and the field in general. Moreover, although the low-level pattern of engagement of ARPIU has been associated with negative health measures in adolescence (Liu et al., 2011) and later in life (Yau et al., 2012), the dichotomous categorization may dilute the effects by grouping together individuals with more and less severe patterns of behavior. Future work employing measures with more dimensions (e.g., distinguishing at-risk from more severe PIU in larger sample) may generate a better understanding of PIU and its underlying neural mechanisms. Fourth, Internet use is a heterogeneous construct and the contexts may differently engage cognitive, behavioral, and affective systems. Future studies examining and comparing different contexts (i.e., online gaming vs. social networking vs. academics vs. other uses) and potential gender differences in context preference (e.g., males may engage more heavily in online games) are warranted. In particular, as Internet gaming disorder has been included in Section III of the DSM-5 (American Psychiatric Association, 2013), assessing for this condition in future studies is warranted.

Conclusion

This study provides new data for understanding the relationship between ARPIU and brain function underlying risk-taking. Importantly, relatively diminished FRN and P300 amplitudes among ARPIU (versus non-ARPIU) adolescents indicate blunted responding in both early and late feedback processing, respectively. ERPs may therefore serve as biomarkers for PIU and help in differentiating normative from dysfunctional behavior. These findings may guide future research on PIU behaviors and assist in determining whether these behaviors follow from abnormal responses to positive/reward and negative/loss stimuli. Future studies that deconstruct the processes underlying ARPIU are important for understanding this group of individuals and possibly identifying individuals at elevated risk for developing PIU. Such research could also provide data helpful in understanding similarities and differences between PIU and non-Internet-based psychiatric conditions, including addictive disorders.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Abbreviations

PIU	Problematic Internet Use
ARPIU	At-risk Problematic Internet Use
SUDs	Substance Use Disorders
ACC	Anterior Cingulate Cortex
ERPs	Event-Related Potentials
FRN	Feedback-Related Negativity
BART	Balloon Analogue Risk Task
UPPS	UPPS Impulsive Behavior Scale
OAR	Ocular Artifact Removal

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Highlights

- Examined relationship between ARPIU and ERPs related to feedback evaluation
- Attenuated ERP amplitudes among ARPIU adolescents during behavioral risk-task
- Attenuated ERP amplitudes suggest decreased sensitivity to feedback
- Feedback-related ERPs (specifically FRN and P300) may serve as biomarkers for PIU

Figure 1.
Grand average ERP for ARPIU and non-ARPIU groups at the electrode channels 11, 12, 5, and 6.

Figure 2. Topographical distribution of the current source density (CSD) of the FRN (200–300ms) associated with reward and loss for the ARPIU and non-ARPIU groups

Figure 3. Grand average ERP for ARPIU and non-ARPIU groups at the electrode channels 62, 67, 72, and 77.

Figure 4. Topographical distribution of the current source density (CSD) of the P300 (300–450ms) associated with reward and loss for the ARPIU and non-ARPIU groups