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Psychometric properties of neural responses to monetary and social rewards across development☆

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ABSTRACT

Reward-related event-related potentials (ERPs) are often used to index individual differences that signal the presence or predict the onset of psychopathology. However, relatively little research has explored the psychometric properties of reward-related ERPs. Without understanding their psychometric properties, the value of using ERPs as biomarkers for psychopathology is limited. The present study, therefore, sought to establish the internal consistency reliability and convergent validity of the reward positivity (RewP) and feedback negativity (FN) elicited by two types of incentives commonly used in individual differences research – monetary and social rewards. A large, developmentally-diverse sample completed a forced-choice guessing task in which they won or lost money, as well as a social interaction task in which they received acceptance and rejection feedback. Data were analyzed at both Cz and at a frontocentral region of interest (ROI) using techniques derived from classical test theory and generalizability theory. Results demonstrated good to excellent internal consistency of the RewP and FN within 20 trials in both tasks, in addition to convergent validity between the two tasks. Results from a regression-based approach to isolating activity specific to a single response demonstrated acceptable to good internal consistency within 20 trials in both tasks, while a subtraction-based approach (ΔRewP) did not achieve acceptable internal consistency in either task. Internal consistency was not moderated by age and did not differ between Cz and the frontocentral ROI; however, the magnitudes of the RewP and FN were significantly associated with age at Cz but not at the ROI. This work replicates previous studies demonstrating good psychometric properties of the monetary RewP/FN and provides novel information about the psychometric properties of the social RewP/FN. These data support the use of reward-related ERPs elicited by multiple reward types in studies of biomarkers of psychopathology.

1. Introduction

Interest in studying and classifying abnormal human functioning using neuroscientific techniques has increased dramatically in the past decade. In line with this, the National Institute of Mental Health created the Research Domain Criteria (RDoC) framework in hopes of identifying the pathophysiology of psychopathology using tools from neuroscience and genomics (Insel et al., 2010). While traditional categorical diagnostic systems have demonstrated reliability (i.e., consistency or precision in measurement; Brown et al., 2001; Regier et al., 2013), the RDoC initiative was motivated, in part, by the questionable validity (i.e., the extent to which a concept or measurement corresponds to reality) of existing classification systems (Boyd et al., 1984; Kendell and Jablensky, 2003; Waszczuk et al., 2017; Widiger and Samuel, 2005). This new framework is an attempt to improve validity by describing continuous variation in functioning, irrespective of diagnostic categories, across multiple levels of analysis, including neural response (Cuthbert and Kozak, 2013). However, although reliability constrains the validity of individual difference measures, relatively little research to date has been conducted to evaluate the reliability of these "new" measures of psychopathology derived from clinical neuroscience.

Event-related potentials (ERPs) are commonly used to identify associations between neural responses and psychopathology. Individual differences in ERPs have been robustly associated with several disorders including depression (e.g., Liu et al., 2014), generalized anxiety disorder (e.g., Weinberg et al., 2010), obsessive compulsive disorder (e.g., Gehring et al., 2000), and schizophrenia (e.g., Horan et al., 2012). Only recently, however, has the field of clinical neuroscience begun to investigate the psychometric properties of these biomarkers, and much of this work has focused on neural responses to errors (Baldwin et al.,

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2015; Foti et al., 2013; Meyer et al., 2017; Meyer et al., 2013; Riesel et al., 2013; Weinberg and Hajcak, 2011). The psychometric properties of other frequently-measured neural responses, such as neural responses to rewards, have received relatively less attention. Yet abnormal neural responses to rewards are characteristic of multiple forms of psychopathology (Baskin-Sommers and Foti, 2015; Benson et al., 2015; Chau et al., 2004; Dichter et al., 2012; Koob and Le Moal, 2001), and reward-related ERPs have been associated not only with current symptoms of psychopathology (Foti and Hajcak, 2009; Liu et al., 2014), but also with *risk* for psychological dysfunction (Bress et al., 2015; Kujawa et al., 2014b; Weinberg et al., 2015a), suggesting that these ERPs may be important biomarkers of psychopathology (Gottesman and Gould, 2003). Consistent with this, reward-related ERPs are included in the Positive Valence Systems of the RDoC matrix, and will therefore be a key avenue of continued research focus.

However, although the psychometric properties of associated symptom measures have been extensively studied (Caci et al., 2007; Carver and White, 1994; Franken et al., 2005; Muller and Wytykowska, 2005; Torrubia et al., 2001; Van den Berg et al., 2010), we know less about the reliability, stability, and validity of reward-related ERPs as measures of psychopathology. The danger in this, then, is that unappreciated psychometric weaknesses of our laboratory and brain-based measures may impose limits on this field of research. In order to understand the neurobiology of mental illness and to identify clinically-useful biomarkers, it will be critical to understand the psychometric properties of existing measurement tools (Baldwin et al., 2015; Barch and Mathalon, 2011; Hajcak et al., 2017; Lilienfeld, 2014).

Recent work has sought to address these problems. Several studies have focused on the psychometric properties of two reward-related ERPs: the reward positivity (RewP), a positive-going deflection in the ERP waveform in response to favorable outcomes that is typically maximal between 250 and 350 ms following stimulus onset at fronto-central recording sites, and the feedback negativity (FN), a negative deflection in the ERP waveform following unfavorable outcomes occurring in the same time-window and at the same sites (Gehring and Willoughby, 2002; Hajcak et al., 2006; Miltner et al., 1997; Proudfit, 2015; Santesso et al., 2008; Yeung et al., 2004). While previous research has often considered the RewP and FN to be variants of the same component, some evidence suggests that these components represent two distinct processes (Foti et al., 2015; Webb et al., 2017), thereby justifying the evaluation of the psychometric properties of both responses.

Some studies have demonstrated good psychometric properties of the RewP and FN. For instance, test-retest reliability, or consistency in measurement at multiple time-points, is necessary to determine whether changes in ERP magnitudes over time are meaningfully associated with factors such as onset of, or recovery from, psychopathology. Acceptable test-retest reliability (Cicchetti, 1994) has been demonstrated for the RewP and FN in sessions separated by less than one day (Segalowitz et al., 2010; FCz: $r_{\text{RewP}} = 0.71$, $r_{\text{FN}} = 0.72$; Fz: $r_{\text{FN}} = 0.84$) and by one week (Levinson et al., 2017; FCz: $r_{\text{FN}} = 0.71$). Other studies have examined the internal consistency reliability (hereafter referred to as "internal consistency"), or similarity in ERP measurements across trials within the same session, of the RewP and FN. Since a measure cannot correlate better with a different measure than it correlates with itself, internal consistency of an ERP constitutes a ceiling for how well that ERP can correlate with individual differences in psychopathology. Acceptable internal consistency has been demonstrated for both the RewP and FN (Levinson et al., 2017; Luking et al., 2017; Marco-Pallares et al., 2011; $\alpha\text{s} > 0.70$).

Additionally, most studies are interested not only in the magnitude of reward- and nonreward-related ERPs, but also the degree to which individuals differentiate rewards from nonrewards under different experimental conditions, or according to individual differences. To do this, the ΔRewP (reward minus nonreward difference) or the ΔFN (nonreward minus reward difference) is often calculated in an attempt to isolate activity specific to one process. However, condition-related averages (e.g., the RewP and FN) are highly intercorrelated (Bress et al., 2012), and so it has been suggested that difference scores are an ineffective method of controlling for neural activity unrelated to the process of interest (e.g., reward processing). In other words, the ΔRewP is correlated with both the RewP and FN, and so the ΔRewP cannot be considered a measure of reward processing that is *independent* of the FN (Meyer et al., 2017). Additionally, of the studies that examined the psychometric properties of the ΔRewP, most reported that the ΔRewP exhibited poor test-retest reliability and internal consistency (Bress et al., 2015; Levinson et al., 2017; Luking et al., 2017). To address these issues, some studies have used a regression-based technique in which the variance remaining (regression residuals) in a regression equation modeling one ERP (e.g., FN) as a predictor of the other (e.g., RewP) is used as a measure of activity unique to the response of interest (e.g., MacNamara et al., 2016; Meyer et al., 2017; Weinberg et al., 2015b). In an examination of the psychometric properties of these scores, Luking et al. (2017) found that residual-based measures performed better than subtraction-based measures, in terms of internal consistency, but still worse than the RewP and FN individually.

These foundational psychometric studies support the use of reward-related ERPs as biomarkers of psychopathology. However, all of these studies were conducted on neural response to monetary incentives. Monetary rewards are salient and easily manipulated, which makes them ideal for use in laboratory settings, but other types of reinforcers also powerfully influence our behaviors. While evidence suggests different categories of rewards elicit responses from overlapping brain regions, it has also been demonstrated that patterns of neural activation are not identical across reward types and may be sensitive to individual and/or developmental differences (Chan et al., 2016; Rademacher et al., 2010; Sescousse et al., 2013; Spreckelmeyer et al., 2009). If the RewP/FN are tapping domain-general reward processing, then RewPs/FNs elicited by different tasks and different reward types should be significantly associated with one another (i.e., they would demonstrate convergent validity), but it is unclear if this is the case (Ethridge et al., 2017). Moreover, the same ERPs measured in different tasks can have different properties, and in particular, different psychometric properties (Foti et al., 2013; Meyer et al., 2013; Riesel et al., 2013). It is essential, therefore, that the psychometric properties, including internal consistency and convergent validity, of the RewP and FN be evaluated across different tasks and reward modalities.

An emerging body of research suggests that neural responses to *social* rewards are relevant to understanding the pathogenesis of mental illness, and are perhaps particularly relevant to the emergence of psychopathology across development (Forbes and Dahl, 2012; Kujawa et al., 2017; Olino et al., 2015; Trezza et al., 2011). Studies that have directly compared neural responses to monetary and social rewards have found that monetary and social rewards recruit both overlapping and distinct neural regions (Izuma et al., 2008; Lin et al., 2012; Rademacher et al., 2010; Saxe and Haushofer, 2008). Recently, we used temporospatial principal components analysis to examine the RewP and FN elicited in a monetary and a social reward task in early adolescents and emerging adults (Ethridge et al., 2017). We found that the two tasks elicited recognizable RewPs/FNs that were similar in timing and topography, and that components across tasks were modestly correlated with one another. However, the ΔRewPs elicited by each task were not significantly correlated in either age group, suggesting that the components are not tapping identical constructs, and may relate in unique ways to individual difference measures (Ethridge et al., 2017). This latter finding must be interpreted cautiously considering the poor internal consistency of the ΔRewP (Bress et al., 2015; Levinson et al., 2017; Luking et al., 2017); nonetheless, this evidence further suggests that evaluating the psychometric properties of neural response to rewards across multiple tasks is necessary.

Finally, there are important developmental changes in the neural circuitry underlying neural response to rewards (Casey et al., 2008;