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Utilizing electroencephalography (EEG) to investigate positive affect☆

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Electroencephalography (EEG) is a widespread neurophysiological measure used to study cognition, emotion and their interaction. There is a strong history and a growing body of EEG research investigating positive affect (PA). In the current article, we focus on EEG components which are increasingly informing the science of PA. We review EEG frequency evidence from alpha-band (recorded over lateral prefrontal leads) and beta-band (over the motor and pre-motor cortex) as measures of approach motivation in PA. We also review evidence of the event-related potential called the Reward Positivity, and the frequency components underlying it in the context of reward processing and learning. These EEG measures have been highly informative of PA, however, they are but a few of the potential EEG measures informing the study of PA.

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Electroencepalography (EEG) is a powerful neurophysiological technique to explore affect, using a millisecond time resolution. In the current article, we focus on the state-of-the-art EEG measures of positive affect (PA). Before introducing them, we feel it is important to define our terms. Affect is a broad term that encompasses emotion and mood, and it reflects the subjective feeling state (affective valence) of an emotion. Motivation, and specifically approach motivation is an important component associated with PA and is the internal state of the organism that reflects the impetus or energy it will expend to accomplish something [1].

Importantly, while intuitively PA goes along with approach motivation, motivational direction and affective valence are not always confounded (e.g. approach-motivated anger). More specifically, PA can vary in approach motivational intensity depending on the stage of goal pursuit [2]. For example, some PAs are high in approach-motivational intensity and occur during the pursuit of a goal. These states likely prepare an individual to act. Other PAs are low in approach-motivational intensity and occur after a goal has been achieved. Finally, PA is usually studied at two levels, the level of general behavioral tendencies (i.e. personality traits) and at the level of current affective states (i.e. emotion and mood). By considering both components of PA, that is, affective valence and approach-motivational intensity, as well as by parallelizing findings from trait and state levels, the current review provides a consistent description on how each of the introduced EEG measures relates to different dimensions of PA.

EEG has been frequently applied to research on PA. EEG allows researchers to extract the summation of large clusters of postsynaptic electrical potentials at the scalp level. The complex patterns of electrical brain activity are then related to psychological states, specific events (either externally driven or internally generated), or behavioral manifestations. Usually, the EEG signal is not recorded from one location only, but high-density montages are used routinely nowadays, which allows for the collection of brain activity at multiple sites simultaneously, and yields complex/multi-dimensional data sets. The EEG signal is extremely rich, but most work examines it using either time-domain or time-frequency analyses. The event-related potential (ERP) is a time domain analysis corresponding to small-amplitude phase-locked and time-locked neural events. They are characterized by electrophysiological properties (including latency, amplitude, polarity, topography and neural sources). Alternatively, time-frequency decompositions of the EEG signal

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are performed to determine frequency spectra and to extract pre-determined frequency bands, including delta, theta, alpha or gamma.

Using EEG to study PA

A large body of EEG studies suggests that specific ERP components and well-defined EEG oscillations (both during active processing and at rest) shed light on the influence of PA on information processing in the human brain. Instead of being merely redundant or mutually exclusive, the variety of ERP and frequency components inform about possible facets of PA. The scientific understanding of PA has greatly benefited from the use of multiple neurophysiological indices concurrently, as opposed to focusing on only one exclusively. No one EEG correlate of PA is sufficient to unpack the complexity of PA, but when considering multiple EEG correlates of PA, different pieces of the puzzle come together to create a meaningful picture.

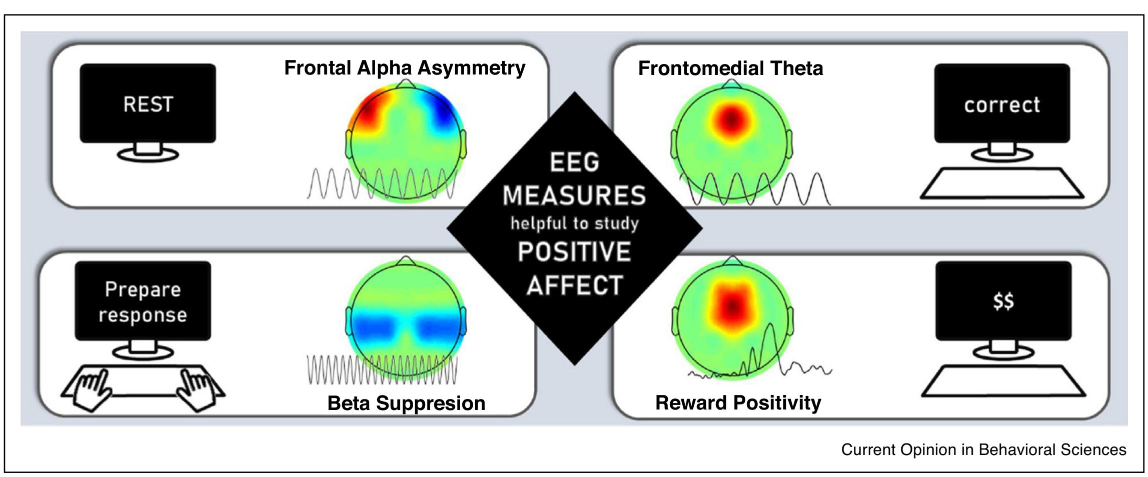
We highlight evidence of how past EEG work has informed our understanding of PA at different levels. In the following, we focus on four EEG measures that have been used to (1) test the validity of a broad underlying valence/motivational system (alpha-band recorded over lateral prefrontal leads), (2) quantify the motivation to act and approach (beta-band over the motor and premotor cortex), (3) study the influence of positive affect on information processing (frontal theta-band) as well as (4) probing the role of positive affect in reward processing and learning (Reward Positivity) (Figure 1).

Frontal alpha asymmetry: measuring positive valence and approach motivation

Much affective research has examined asymmetric frontal cortical activity. Predominantly, EEG is used to assess asymmetric frontal cortical activity comparing alpha power (8–13 Hz) activity levels between the left and right frontal sites. Alpha power is inversely related to regional brain activity as suggested by hemodynamic and behavioral measures [3]. EEG frontal asymmetry typically uses difference scores, based on the premise that one hemisphere may be inhibiting the opposite hemisphere [4]. EEG frontal asymmetry can be examined as a ‘resting’ baseline measure or as an active state measure. Baseline measures are typically recorded when an individual sits quietly for about 4–8 min, alternating eyes open and closed each minute. This type of frontal asymmetry is thought to reflect a trait-like individual difference measure [5]. To establish more causal evidence, other research has manipulated asymmetric frontal cortical activity through affective tasks or examined the influence of manipulations of cortical activity on affective variables [6].

Based on this EEG work, a large number of studies have found that greater relative left frontal activity is associated with the experience of PA, whereas greater relative right frontal activity is associated with the experience of negative affect (NA). This line of research suggests that the experience of PA or NA (affective valence) is the influencing factor of asymmetric frontal cortical activity. This model is typically called the valence model of frontal asymmetry and fits affective evidence when PAs are associated with approach motivation and NAs are associated with withdrawal motivation. However, other studies comparing low versus high approach-motivated PA have revealed that high approach-motivated PA is associated with greater relative left frontal activity than low approach-motivated PA (see Ref. [7••] for review). This growing evidence supports a model that motivational direction,

Figure 1



Schematic of the EEG measures that can be used to study positive affect. Overview of the four main EEG measures discussed in this review.

rather than affective valence is driving frontal asymmetry. Specifically, that greater relative left frontal activity is associated with approach motivated states and traits. Greater relative right frontal activity is associated with withdrawal motivated states and with motivational conflict [8]. A motivational distinction of greater relative left frontal asymmetry is important for PA in emotional situations when there is not a one-to-one relationship between approach motivation and PA (e.g. two positive affect states that are high versus low in approach motivation, but are equivalent in positive valence). Other situations occur when relative left frontal activity is increased by manipulations that do not increase PA, such as transcranial direct current stimulation [9]. In sum, both models have relevance to research on PA, but research examining diverse PAs varying in motivational intensity are more consistent with predictions derived from the motivational direction model than the affective valence model.

Beta activity over the motor cortex: measuring approach-motivated motor-preparation

During movement, preparation for movement, and observation of movement, the motor cortex and pre-motor areas of cortex become more active [10]. This increase in activity reduces EEG beta power (13–30 Hz) over the motor and pre-motor cortex. Suppressed beta activity over the motor cortex appears to be a neural correlate of motor-action preparation. For example, increasing beta suppression over the motor cortex is related to faster motor movement [11]. Past work has found that approach motivation enhances motor preparation as measured by reduced beta activity. Both state [12] and trait [13] approach motivation enhance beta suppression.

Beta suppression over the motor cortex appears to be a measure of motor readiness occurring during different motivational states [14•]. Anticipatory and consummatory PAs vary in approach motivational intensity [2]. Positive Affects that occur during pursuit of a goal, tend to be high in approach-motivational intensity. As such, these states likely prepare an individual to act. Positive Affects that occur after a goal has been achieved, tend to be low in approach-motivational intensity. In a recent study, researchers [15,16] directly tested whether high (pregoal) versus low (postgoal) approach-motivated PA states would differ in beta suppression and relate to cognitive processes that facilitate goal pursuit. Results revealed that beta suppression was highest in pregoal positive states, relative to postgoal positive and neutral states. Additionally, greater motor-action preparation in high approach-motivated positive states predicted cognitive narrowing in this and other studies [17,18]. Approach motivated pregoal states enhance neural preparation for motor-action, as well as cognitive processes to facilitate goal pursuit.

Beta suppression may also reflect emotional-based decision making for motivated action processes [19••]. Collectively, these results demonstrate a unique contribution of the motor system in goal pursuit. Beta suppression may be an important indicator of motivated action, and play an important role in decision making for emotion-based decisions, as well as actions.

Reward Positivity, Delta, and Theta: reward processing and learning

Another important line of research in the context of PA focuses on reward processing. While everyone would agree, that encountering something positive feels good, this truism has been only recently formally modeled [20]. Using a computational model approach, it has been shown that participants report to feel better after receiving positive performance feedback or a monetary reward [21•], in particular when this reward was unpredicted [22,23]. The motivation to collect positive experiences is a crucial mechanism for reinforcement learning and adaptive behavior. Because of its excellent temporal precision, EEG has been used extensively to study this rapid (emotional) process. One of the most studied EEG components in reinforcement learning is the Reward Positivity (RewP) [24–26], a positive going fronto-central component, peaking around 250 ms after evaluative feedback. The RewP has been shown to be larger for positive compared to negative performance feedback (e.g. wins versus losses). Moreover, the amplitude of the RewP component has been linked to positive prediction errors, that is, when outcomes are better than expected. EEG/ERP source localization and combined EEG/fMRI analysis have identified the anterior cingulate cortex and the medial prefrontal cortex as likely sources of the RewP [25,26]. Given its close links to reward processing and positive prediction errors [27], one could consider the RewP as a measure of processes that lead to or are integrated in PA.

This consideration is supported by findings linking amplitude of the RewP to motivational and affective changes at both state and trait levels. On a trait level, the RewP is positively related with reward responsiveness [28], positive emotionality [29] and behavioral activation or approach motivation [30]. To study affective and motivational states, different experimental manipulations were used. For example, the amplitude of the RewP is larger in trials where participants can win money or revenge, compared to trials where they can avoid losses or neither [31–33]. Moreover, the RewP seems to scale with the motivational value of the offered reward, increasing with the likeability [34,35] or the amount of money won [36,37]. Additionally, the RewP has been reported to increase with task-irrelevant positive affect induced with positive pictures [38] or an imagery technique [39], however these last results need to be replicated further, as null-results have been reported too [40,41•]. In sum, the

RewP appears to relate to both state and trait measures associated with PA.

More recently, time-frequency analysis of the EEG data instead of classical ERPs gained attention in the context of reward processing. One reason for this is that this approach helps to disentangle different influences of overlapping ERPs (RewP, P3, N2) by parsing the EEG signal into theta (4–8 Hz) and delta (<4 Hz) activity. It has been suggested that activity in the delta band is closely related to the RewP and similarly sensitive to rewards and positive reward prediction errors [42,43]. In comparison, theta was reported to be more sensitive to negative outcomes and unsigned prediction errors [44•,45]. This led to the idea that theta activity could be a signal for the need of augmented control over information processing [46]. While much more work is needed to understand specifics of these EEG components, such as underlying phase locked activity, we would like to point out some studies, which reported affective or motivational modulations of these components. For example, increased delta activity was found when perceived control over the task and outcome was high, a concept somewhat related to approach motivation and PA [47]. By comparison, participants in PA states (induced via guided imagery [39,41•] or reward magnitude [37]) showed reduced theta responses to unexpected monetary reward feedback. This reduced theta activity was interpreted to be the result of changed expectations accompanying affective state: participants in positive mood were not surprised when gaining a reward, reflecting an optimistic bias in positive mood.

Delta and theta oscillations may reflect the synaptic plasticity mechanisms that regulate the daily rhythm of arousal and mood. The daily rhythm of arousal/tiredness and positive/negative emotion are closely related to that of theta/ delta cortical EEG power [48,49]. At a mechanic level, theta increases, and delta decreases synaptic connectivity and thus the theta/delta rhythm contributes to homeostatic plasticity with net synaptic strength remaining constant across days [48,50]. Taken together, RewP, delta and theta activity seem to relate to separate processes during reward processing. Given that PA is not only an effect of exogenous states, but can also influence the perception of exogenous states [21•,23], these markers present themselves as a promising tool to study how changes in PA unfold over time.

Conclusions

EEG has much to offer to the study of PA. EEG measures can (1) inform us about an existing valence or motivational system (such as frontal alpha asymmetry), (2) help to measure the impetus to act (beta suppression), (3) shed light on how PA colors information processing (such as frontal theta) or (3) reflect reward monitoring relevant for PA (such as the RewP). The EEG measure reviewed above are but a small portion of the signal recorded using EEG, and moreover, they are often used in isolation. Accordingly, attempts made to explore and model effects of PA on cognition and emotion when multiple EEG correlates are considered concurrently could represent a critical step in better understanding the nature and function of affective states. Simultaneously, the presented markers are not necessarily specific to positive affect, as frontal alpha asymmetry can occur in a negative affective state high in approach motivation (such as anger). Consequently, none of the EEG measures presented here can currently be understood as a direct marker or a manifestation of an underlying valence system. Nevertheless, considering a complex pattern across different EEG measures could help to inform about different components of PA when individuals are unable, or unwilling to accurately report of these motivational processes. The benefits of using EEG to study PA extend beyond those offered by other neural and physiological measures in their affordability, rapid time resolution, and minimal invasion. The current article reviewed robust signals associated with or sensitive to PA. In this context, we believe that much more exciting EEG research is yet to come on the study of PA, not only in humans, but non-human animals as well.

Conflict of interest statement

Nothing declared.

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