Developmental Psychology
2009, Vol. 45, No. 2, 525–533

0012-1649/09/$12.00 DOI: 10.1037/a0014576

Dynamic Variation in Pleasure in Children Predicts Nonlinear Change in Lateral Frontal Brain Electrical Activity

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Individual variation in the experience and expression of pleasure may relate to differential patterns of lateral frontal activity. Brain electrical measures have been used to study the asymmetric involvement of lateral frontal cortex in positive emotion, but the excellent time resolution of these measures has not been used to capture second-by-second changes in ongoing emotion until now. The relationship between pleasure and second-by-second lateral frontal activity was examined with the use of hierarchical linear modeling in a sample of 128 children ages 6–10 years. Electroencephalographic activity was recorded during "pop-out toy," a standardized task that elicits pleasure. The task consisted of 3 epochs: an anticipation period sandwiched between 2 play periods. The amount of pleasure expressed during the task predicted the pattern of nonlinear change in lateral frontal activity. Children who expressed increasing amounts of pleasure during the task exhibited increasing left lateral frontal activity during the task, whereas children who expressed contentment exhibited increasing right/decreasing left activity. These findings indicate that task-dependent changes in pleasure relate to dynamic, nonlinear changes in lateral frontal activity as the task unfolds.

Keywords: pleasure, EEG, lateral frontal cortex

Pleasure, the euphoric feeling that can occur as a result of the internal representation of hedonic information, is an important ingredient of positive affect (Klein, 1987; Meehl, 1975). Activity in subcortical brain structures and various regions of the prefrontal cortex relate to the occurrence of pleasure (Berridge, 2003; Gable & Harmon-Jones, 2008; Leon & Shadlen, 1999).

Specifically, the ability to consciously experience pleasure relates to abilities to (a) internally represent hedonic information and (b) translate represented hedonic information into conscious positive emotional experience; these processes are likely subserved by prefrontal cortex activity. For example, recent neuroimaging data indicate that activity in several prefrontal regions contributes to positive affect, including in the dorsolateral prefrontal cortex (Wallis & Miller, 2003), orbitofrontal prefrontal cortex (Kringelbach, 2005), ventromedial prefrontal cortex (Hamann, Ely, Hoffman, & Kilts, 2002), and frontopolar prefrontal cortex (Pochon et al., 2002). In particular, it is likely that the representational (e.g., the ability to represent the hedonic value of four drops of a sweet liquid versus eight drops), executive (e.g., enacting a plan to obtain a reward), and working memory functions subserved by activity in the frontal cortex—particularly the lateral prefrontal cortex—contribute to pleasure capacity (Hikosaka & Watanabe, 2000; Kobayashi, Lauwereyns, Koizumi, Sakagami, & Hikosaka, 2002; Pochon et al., 2002; Schultz, 2006; Watanabe, 1996).

In addition to neuroimaging techniques, brain electrical (i.e., electroencephalographic; EEG) measures of frontal function have been extensively used to examine relations between baseline levels of frontal activity and the propensity to experience certain emotional states. Specifically, the left and right frontal regions of the cerebral hemisphere are differentially involved in the expression of approach-related emotions and withdrawal-related emotions, respectively (Davidson, 1992; Davidson, 2004a; Harmon-Jones, 2003; Urry et al., 2004; Wheeler, Davidson, & Tomarken, 1993). For example, the tendency to experience pleasure in response to pleasant stimuli has been linked to asymmetrical activity in the frontal cortices; infants respond to sweet tastes with increased relative left frontal activity (Fox & Davidson, 1986), exhibit greater relative left-sided frontal activity in response to happy video clips (Davidson & Fox, 1982), and exhibit greater relative left frontal activity during facial displays of joy (Fox & Davidson, 1988). Furthermore, adults who enjoy eating desserts to a great extent exhibit greater relative left frontal activity when they view pictures of desserts compared with when they view pictures of neutral pictures (Gable & Harmon-Jones, 2008).

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This research was supported in part by National Institute of Mental Health Institutional Training Grant T32-MH18931. This research was also supported by National Institute of Mental Health Grant P50-MH069315. We thank Andrew T. Herdina for his contribution to this research project, and we thank those children who participated in this study.

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A neglected yet relevant aspect of the approach–withdrawal hypothesis of frontal EEG asymmetry is the idea that shifts in frontal asymmetry may not only mark the onset of approach-related versus withdrawal-related emotional states but also carry information about whether the emotional state the individual is in is more internally focused (introspective) or externally focused. Specifically, given the positive relationship between greater relative right frontal activity and the experience of withdrawal-related emotions, it seems that the types of emotions that are represented by greater relative right frontal activity would include negative *and* positive emotions that are more internally focused and pensive, such as sadness and contentment (*contentment* can be defined as "a calm form of happiness"). In contrast, the types of negative and positive emotions represented by greater relative left frontal activity are generally intense, action oriented, and driven by external stimulation (e.g., exuberance and anger). One half of the equation has been well articulated; adults exhibit greater relative left frontal activity when angry (Harmon-Jones, 2003). To build upon this work, it seems warranted to investigate whether individual variation in the tendency to express high-intensity forms of pleasure versus lower intensity forms of pleasure relate differentially to lateral frontal asymmetries. If there is an externally focused/internally focused facet to the relationship between frontal EEG asymmetry and approach- and withdrawal-related emotions, we would expect to find that different intensities of pleasure would relate to different patterns of left and right frontal asymmetry. Specifically, if right frontal activity relates to withdrawal-related or "low approach-related" emotions that are internally focused and pensive, then greater relative right frontal activity should relate to contentment. Why contentment? Contentment is a positive emotional state that (a) is intrapsychic and characterized by the occurrence of pleasant reveries, (b) generally involves a less dramatic outward display of positive emotion (i.e., contentment is more likely to be characterized by less intense facial signs of pleasure, such as non-Duchenne smiles, compared with higher intensity positive emotions such as exuberance), and (c) is not heavily action oriented. There is evidence in the literature to support this hypothesis. Namely, positive emotion characterized by non-Duchenne smiles relates to greater relative right frontal activity in adults (Ekman, Davidson, & Friesen, 1990). Furthermore, a greater contentment-related pleasure capacity at age 4 relates to greater relative right frontal asymmetry at age 8 (Kim & Bell, 2006).

The excellent time resolution of brain electrical measures—compared with the coarser time resolution of functional magnetic resonance imaging and positron emission tomography—seems particularly well suited for assisting in the investigation of the physiological correlates of individual differences in pleasure expression. Though electrical activity recorded from the scalp does not correspond exactly to behavioral changes, it is a measure that is well suited to capture the dynamic changes in pleasure that occur over the course of an extended pleasure-inducing task that takes place over a span of minutes. Therefore, we investigated the extent to which the growth, decay, or maintenance of contentment versus happiness over time relates to concomitant second-by-second asymmetry in lateral frontal brain electrical activity. EEG activity was recorded while children completed a "pop-out toy" task (Pfeifer, Goldsmith, Davidson, & Rickman, 2002), a task that normatively induces pleasure in children and comprises three epochs. The child played an arousing game with the experimenter during the first epoch of the task ("game played with experimenter"). An anticipation period, during which the child sat in a room alone and waited to play the game with his or her parent, made up the second epoch ("anticipation"). The child played the game and surprised his or her parent during the last epoch ("game played with parent"). Each child was video recorded during the "pop-out toy" task so that pleasure could be quantified from behavior and tracked for each child. *Pleasure* scores were used to predict the second-by-second lateral frontal EEG asymmetry trajectory during the "pop-out toy" task. On the basis of extensive prior research and theory (Davidson, 2004b), we hypothesized that the expression of intense pleasure would be related to greater acceleration of left lateral frontal activity. The hypothesis that frontal activity in general, and lateral frontal activity in particular, may track task-dependent pleasure gains footing when it is considered in conjunction with previous research showing that activity in the lateral frontal cortex relates to the online manipulation of task-dependent information (Christoff & Gabrieli, 2000; Crone, Wendelken, Donohue, van Leijenhorst, & Bunge, 2006). These findings lend support to the view that activity in the lateral frontal cortex plays an important role in tracking incoming hedonic information. In order for a positive affective state to take hold, it seems likely that hedonic information must be internally represented and kept in a highly accessible state.

Method

Participants

Families were recruited from state birth records, supplemented by advertising in the local area. Children with major health problems and developmental disabilities were excluded. We did not select for risk for psychopathology. One-hundred and twenty-eight individual members of twin pairs ages 6–10 years old contributed data, but only 103 children were right-handed and had usable electrophysiological data. (One child from each twin pair was randomly selected for inclusion in this analysis. Each child included in the analyses presented in this report had a twin who completed the same testing, but data from each of the cotwins have not been analyzed and are not included in this report.) The 103 cases of usable data included 53 girls, eight 6-year-olds, twenty-two 7-year-olds, forty-four 8-year-olds, twenty-four 9-year-olds, and five 10-year-olds (*M* age = 7.96; *SD* = 0.98). There were 100 Caucasian children, 1 African American child, 1 Asian American child, and 1 Hispanic child. The Hollingshead Index was used to determine the socioeconomic status of each family (Hollingshead & Redlich, 1958). For this sample, the mean Hollingshead Index score was 45.86 (*SD* = 9.58), and the mean class score was 2.18 (*SD* = 0.81).

Measurement of Pleasure

The "pop-out toy" task is from the Laboratory Temperament Assessment Battery (Pfeifer et al., 2002). During the "pop-out toy" task, pleasure was elicited in children when they played a game with an experimenter and then with their parent. The task consisted of three segments. Each child engaged in each one of the three segments of the "pop-out toy" task only once. The game began when the experimenter presented the child with a can that resembled a can of edible nuts. (The can actually contained a spring-loaded toy that popped out when opened.) The experimenter opened the can with the child to reveal its contents. (Children were generally surprised and exuded some degree of pleasure at this point.) This set of events made up Epoch 1 ("game played with experimenter"). At the very end of Epoch 1, the experimenter gave the child instructions on how to play the same game with his or her parent, and this generally evoked additional positive emotion from the child. The child was left alone in the room with the toy while the experimenter went to get the parent. This sequence of events made up Epoch 2 ("anticipation"). Finally, the parent, who was unaware of the surprise in the can, entered the room, and the child popped the toy with his or her parent. This last series of events made up Epoch 3 ("game played with parent").

A *pleasure* score was generated for each child for each epoch of the "pop-out toy" task. Each *pleasure* score was based on ratings made by trained coders. Two separately scored indices were combined to derive one *pleasure* score for each child during each of the three epochs: Smiles were rated on intensity/duration with a 0 (*smiling absent*) to 3 (*intense or long lasting smiling*) scale; vocal/facial/bodily pleasure (positive vocalizations, cheeks, eyes, etc.) were rated separately on a 0 (*behavior absent*) to 3 (*behavior present to a strong degree*) scale. Each of the two factors contributed equally to the final *pleasure* score. In total, the *pleasure* scores reflect the magnitude of the child's smiles and the degree of positive affect expressed vocally, facially, and/or physically by the child. *Pleasure* scores ranged from 0 (*pleasure absent*) to 3 (*extreme pleasure*). The interrater reliability was high for this measure, with a kappa value of .72. All coders were graduate-level or undergraduate-level research assistants trained to score vocal, facial, and bodily indicators of emotion by experienced graduate-level coders. During this training process, potential coders had to practice scoring videotaped cases that had already been scored by one or more experienced "master" graduate-level coders. Once novice coders reached a level of reliability with the "master" graduate-level coders, the coder was allowed to score actual, unscored data. We chose to verify the accuracy of behavioral coding by randomly subjecting coders to reliability testing. Roughly half (55) of the cases were double coded (i.e., coded by a nonmaster coder and a master coder) in order to ensure that nonmaster coders remained at a stable level of reliable scoring over time.

Given our interest in determining whether individual differences (1) exist in pleasure responsivity in vivo during a pleasure-inducing task, and (2) relate to individual differences in lateral frontal activity, we divided the sample into *mild pleasure*, *moderate pleasure*, and *intense pleasure* groups on the basis of the children's emotional reactivity during the "game played with parent" (Epoch 3) segment of the task because that portion of the task was best suited for capturing individual differences in pleasure since it was the portion of the task that induced the widest spread in positive emotional expression between individual children. Therefore, a *mild pleasure*, a *moderate pleasure*, and an *intense pleasure* group were created. All children in the *mild pleasure* group had earned a *pleasure* score of 1.5 or less during "game played with parent" (Epoch 3). All children in the *moderate pleasure* group had earned a *pleasure* score greater than 1.5 but less than 2.5 during "game played with parent" (Epoch 3), and all children in the *intense pleasure* group had earned a *pleasure* score greater than or equal to 2.5 during "game played with parent" (Epoch 3). The mean *pleasure* score for each group across all three epochs was as follows: *mild pleasure* group, *M pleasure* score = 1.39 (*SD* = 0.23); *moderate pleasure* group, *M pleasure* score = 2.10 (*SD* = 0.20); and *intense pleasure* group, *M pleasure* score = 2.64 (*SD* = 0.22).

None of the children in the sample earned a pleasure score of 0 during the "game played with parent" segment of the task. The only time any child failed to show any quantifiable positive emotion (i.e., earning a *pleasure* score of 0) was during the "anticipation" segment of the task, and the one child who earned a pleasure score of 0 during the "anticipation" segment of the task was included in the *mild pleasure* group.

EEG Acquisition and Analysis

Twenty-nine channels of EEG activity were recorded (using a stretch lycra electrode cap based on the 10–20 electrode system. EEG activity was recorded from FP1/2, FPF1/2, F3/4, F7/F8, FC3/4, FC7/8, F3/4, C3/4, T3/4, T5/6, CP3/4, CP5/6, P3/4, PO3/4, and a ground electrode mounted between FZ and CZ. Our intention was to identify frontal regions that showed a unique relationship with pleasure. On the basis of prior data in the EEG literature showing relations between variations in lateral (F7/F8) frontal activity and emotion, we selected this frontal region for analysis. EEG from the identical time points in the parietal region (P3/P4) was selected as a comparison to determine the specificity of our findings to the frontal region. We collected eight 1-min trials of resting EEG data referenced online to physically linked ears (gain = 20K), four with eyes open and four with eyes closed, in one of two counterbalanced orders. EEG electrode impedances were less than 5KΩ. Eye movement and muscle artifact were removed via a regression equation fit to the raw EEG data, and a low-pass filter of 200 Hz was applied (i.e., all frequencies below 200 Hz were passed). In addition, each child's EEG data was hand scored in order to check for and remove any missed EEG artifact. Alpha (8–13 Hz) power values were computed for the lateral frontal (F7/8) and parietal (P3/4) sites. On average, children tend to exhibit reliable EEG activity at a frequency of 8 Hz by the time they are 2 years old, which reaches an average maximum of about 10 Hz by the time the child is 10 years old (Davidson, Jackson, & Larsen, 2000; Niedermeyer, 1997). Therefore, given that the bulk of the sample consisted of 7–9-year-olds, we felt that the frequency band of 8–13 Hz was adequate because it is likely that the vast majority of these children exhibit adultlike patterns of alpha activity by this stage of development. The power values calculated were based on all of the artifact-free, 1-s units of EEG data with an off-line whole-head average reference and a fast Hartley transform. Across all children, the average length of the "game played with experimenter" (Epoch 1) segment of the task equaled 38.39 s. On average, 75% (*SD* = 26%) of the lateral frontal and 84% (*SD* = 21%) of the parietal 1-s units that made up Epoch 1 were usable. The average length of "anticipation" equaled 44.11 s. On average, 77% (*SD* = 27%) of the lateral frontal and 86% (*SD* = 20%) of the parietal 1-s units that made up Epoch 2 were usable. The average length of "game played with parent" equaled 25.45 s. On average, 62% (*SD* =

29%) of the lateral frontal and 74% (*SD* = 24%) of the parietal 1-s units that made up Epoch 3 were usable. EEG asymmetry scores were computed by subtracting left alpha values from right alpha values (Log Right – Log Left). Positive asymmetry values indicate greater relative left-sided activation, and negative values indicate greater relative right-sided activation.

Statistical Approach

Hierarchical linear modeling (HLM; Raudenbush, Bryk, Cheong, & Congdon, 2004) was used to chart EEG asymmetry trajectory across the "game played with experimenter," "anticipation," and "game played with parent" segments of the task, with *pleasure* scores predicting individual differences in lateral frontal EEG asymmetry trajectory. HLM is a form of multilevel analysis that can be used to estimate average growth trajectories as well as to characterize the variability of trajectories across individuals. The Level-1 model estimated the association between lateral frontal EEG asymmetry scores and time elapsed from the onset of the "game played with parent" segment of the task. The second-by-second EEG asymmetry scores from each child, collected across the "game played with experimenter," "anticipation," and "game played with parent" segments of the task, made up the Level-1 outcome variable. The shape of the overall (across all children) EEG asymmetry trajectory was modeled as nonlinear. A nonlinear model was chosen because changes in brain electrical activity do not conform to a linear pattern across time (Coan & Allen, 2004). Therefore, the simplest nonlinear model—a quadratic model—was created to accommodate the nonlinearity of EEG asymmetry patterns over time. Each within-epoch quadratic function was treated as a random factor. The linear term that is embedded in the quadratic function was treated as a random factor. Thus, the linear slope was allowed to vary between subjects. The linear term determined the basic EEG asymmetry slope that ran its course from the onset to the offset of the task. The quadratic term within each epoch represented an acceleration/deceleration parameter that accounted for nonlinear change within-epoch. The EEG asymmetry trajectory from onset to offset of the task can be viewed as a compilation of the three quadratic functions that correspond to the "game played with experimenter," "anticipation," and "game played with parent" epochs of the task (These functions were created such that the end point of "game played with experimenter" was mathematically set equal to the start point of "anticipation." This enabled us to graph a continuous, nonsaltatory trajectory across time). Each quadratic term was treated as random to allow for the possibility that EEG asymmetry trajectory might vary between children. The intercept was treated as a fixed factor in order to maximize our ability to discern task-dependent changes in trajectory between children. Without this feature, we would be less able to defend against the possibility that any between-subjects differences in EEG asymmetry trajectory observed across the task were just a reflection of the different EEG asymmetry scores that these children possessed before the task began, with the observed differences in EEG asymmetry trajectory bearing little or no relation to the occurrence of the positive stimulus.

At Level 1, within each epoch, the EEG asymmetry trajectory was characterized as follows:

1. Lateral frontal EEG asymmetry score at time *x* of "game played with experimenter" = P_0 + P_1 (time elapsed from the onset of "game played with experimenter") + P_2 (time elapsed in "game played with experimenter")^2 + error.

2. Lateral frontal EEG asymmetry score at time *y* of "anticipation" = P_0 + P_1 (time elapsed from the onset of "game played with experimenter") + P_2 (total time in "game played with experimenter")^2 + P_3 (time elapsed in "anticipation")^2 + error.

3. Lateral frontal EEG asymmetry score at time *z* of "game played with parent" = P_0 + P_1 (time elapsed from the onset of "game played with experimenter") + P_2 (total time in "game played with experimenter")^2 + P_3 (total time in "anticipation")^2 + P_4 (time elapsed in "game played with parent")^2 + error.

The Level-2 model was built to explain individual differences in EEG asymmetry trajectory. The Level-2 model introduced *pleasure* scores to explain individual differences in the shape of the lateral frontal EEG asymmetry trajectory. These *pleasure* scores came from two sources: (a) "game played with experimenter" and "game played with parent" (*Pleasure* scores from the "anticipation" epoch were excluded because this epoch lacked social interaction; therefore, the *pleasure* score that corresponds to this epoch may be less representative of the type of pleasure evinced during "game played with experimenter" and "game played with parent") and (b) the period immediately preceding the onset of "game played with experimenter." Predictors that were introduced at Level 2 were restricted to variables that preceded a particular portion of the task. For example, only variables that were measurements of pleasure level before the onset of "game played with experimenter" were used to predict lateral frontal EEG asymmetry intercept values. Thus, pretask, "game played with experimenter," and "game played with parent" *pleasure* scores were entered as predictors of P_0, P_1, $P_{3,}$ and P_4. As a statistical comparison, the multilevel model built for the lateral frontal EEG asymmetry data was applied to the parietal (P3/4) EEG asymmetry data. This was done to determine whether *pleasure* scores would predict parietal EEG asymmetry trajectory. If *pleasure* scores predict parietal EEG asymmetry trajectory and lateral frontal EEG asymmetry trajectory in the same way, this would be evidence for a more global brain effect, not a unique lateral frontal effect.

Results

Task-Dependent Pleasure

The total amount of pleasure expressed by each child was quantified by the independent ratings of trained coders who observed the facial, vocal, and physical behavior of each child across all three epochs of the "pop-out toy" task. The *pleasure* scale ranged from 0 (*pleasure absent*) to 3 (*extreme pleasure*). The sample was divided into *mild pleasure* (*M* pleasure score = 1.39, *SD* = 0.23), *moderate pleasure* (*M* pleasure score = 2.10, *SD* = 0.20), and *intense pleasure* (*M* pleasure score = 2.64, *SD* = 0.22) groups. Figure 1 provides an illustration of how the pleasure trajectories of these three *pleasure* groups differed across time. Notably, a significant epoch (*pleasure* during "game played with experimenter"/*pleasure* during "anticipation"/*pleasure* during "game played with parent") by group (*mild pleasure/moderate*

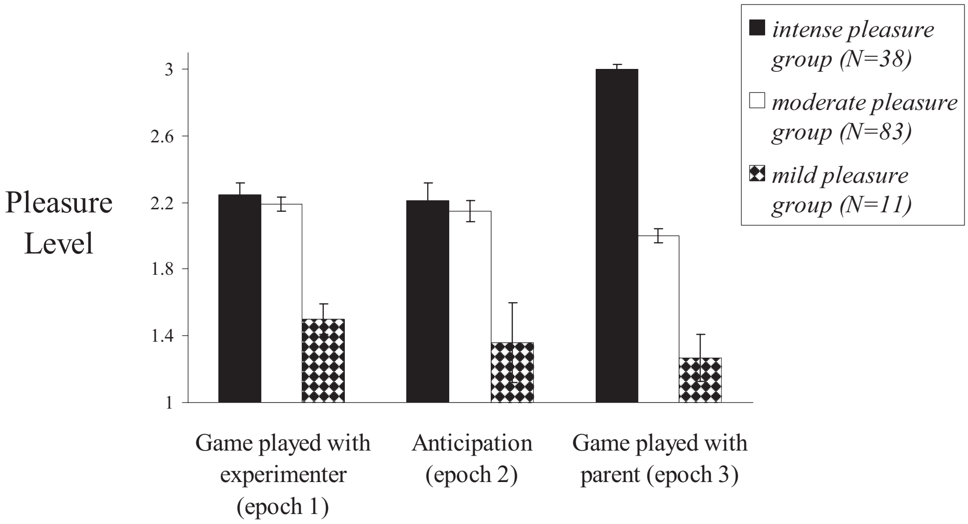

Figure 1. A significant epoch (Epoch 1 *pleasure*/Epoch 2 *pleasure*/Epoch 3 *pleasure*) by group (*mild pleasure/moderate pleasure/intense pleasure*) interaction, $F(2, 127) = 21.37$, $p < .001$, emerged. The *pleasure* scores for children in the *mild pleasure* group did not differ significantly from "game played with experimenter" to "game played with parent," $p > .3$. Similarly, the *pleasure* scores for children in the *moderate pleasure* group did not change significantly across the task from "game played with experimenter" to "game played with parent" ($p > .2$).

pleasure/intense pleasure) interaction, $F(2, 127) = 21.37$, $p < .001$, was present, with children in the *mild* and *moderate pleasure* groups showing no change in the amount of pleasure they expressed during the task (Figure 1; *p*s > .2), whereas children in the *intense pleasure* group showed increasing pleasure across the task. We next examined whether these different pleasure patterns related to differential patterns of second-by-second lateral frontal activity.

Baseline lateral EEG activity recorded before the task began did not predict *pleasure* scores during any of the three epochs of the task (all *p*s > .15).

Second-by-Second Lateral Frontal EEG Asymmetry and Task-Dependent Pleasure

A hierarchical growth curve model was built using lateral frontal (F7/8) second-by-second EEG asymmetry data from each child as a Level-1 outcome variable. "Game played with experimenter" and "game played with parent" *pleasure* scores were used in the Level-2 model to predict individual differences in lateral frontal EEG asymmetry trajectory during the task (Table 1). (The multilevel model used in this analysis was quadratic. Thus, the formula

Table 1
Hierarchical EEG Asymmetry Model for Lateral Frontal Cortex

Model components	β-coefficient estimate	Predictors	Predictor β-coefficient estimate	Approximate degrees of freedom	*p*
β_{00} intercept	1.97×10^{-2}	Pleasure before the onset of "game played with experimenter" (Epoch 1)	8.26×10^{-3}	7825	.27
β_{10} (linear component)	2.24×10^{-4}	Pleasure during "game played with parent" (Epoch 3)	3.19×10^{-4}	101	.18
		Pleasure during "game played with experimenter" (Epoch 1)	4.19×10^{-4}	101	.24
β_{20} (Epoch 1 quadratic component)	$-(1 \times 10^{-5})$	Pleasure during "game played with experimenter" (Epoch 1)	$-(2.7 \times 10^{-5})$	102	.21
β_{30} (Epoch 2 quadratic component)	2×10^{-6}	Pleasure during "game played with experimenter" (Epoch 1)	$-(1.3 \times 10^{-5})$	101	.04*
β_{40} (Epoch 3 quadratic component)	$-(1.3 \times 10^{-5})$	Pleasure during "game played with experimenter" (Epoch 1)	5×10^{-5}	101	.01*
		Pleasure during "game played with parent" (Epoch 3)	$-(1.7 \times 10^{-5})$	101	.42

Note. The multilevel model used in this analysis was quadratic. Thus, the formula used to calculate the lateral frontal EEG asymmetry trajectory included squared terms. All factors were treated as random except for the intercept.
$^* p < .05$.

used to calculate the lateral frontal EEG asymmetry trajectory included squared terms).

Across the sample as a whole, lateral frontal EEG asymmetry differed significantly from onset to offset of the task ($p < .01$), indicating that significant change occurred in lateral EEG asymmetry from “game played with experimenter” to “game played with parent.” Overall, the lateral frontal EEG asymmetry trajectory for the *intense pleasure* group was characterized by a positive growth curve (Figure 2), indicating increasing relative left lateral frontal activation over time. This pattern emerged because the amount of pleasure expressed during “game played with experimenter” positively predicted lateral frontal EEG asymmetry during “game played with parent” ($\beta = 5 \times 10^{-5}$; $p < .05$; Table 1; Figure 2). This neurophysiological pattern corresponded to the behavioral pleasure pattern exhibited by children in the *intense pleasure* group across the task (Figure 1). Thus, left lateral frontal activity appeared to increase on a moment-to-moment basis, with increases in behavioral signs of pleasure as the task evolved.

The negative curvature in the lateral frontal EEG asymmetry trajectory of the *mild pleasure* group during “game played with parent” was due to these children expressing less pleasure during “game played with experimenter” than did children in the *moderate* and *intense pleasure* groups. This neurophysiological pattern seems to be a marker for the propagation of a calm pleasure state into subsequent moments of a task.

The relatively stable pattern of lateral frontal activation exhibited by children in the *moderate pleasure* group contrasted with the *mild pleasure* and *intense pleasure* groups’ pattern. This neurophysiological pattern may mark the propagation of a moderately intense—yet unyielding—pleasure state into subsequent moments of a task.

We conducted additional analyses to determine whether changes in left or right lateral frontal activation might account for the observed shifts in asymmetry score at a between-groups level. We regressed mean whole-head power from the alpha power for the right (F8) and left (F7) lateral frontal electrode site for each child in order to index the alpha power unique to each site (Davidson, Jackson, & Larson, 2000), providing a means to determine whether activity in the left versus right hemisphere contributed to the observed changes in asymmetry score during the task. Then we tested the difference between dependent *r*s using Cohen & Cohen’s (1983) method in order to determine whether the observed positive frontal asymmetry in the *intense pleasure* group was driven by (a) increasing left frontal activity, (b) decreasing right activity, or (c) both increasing left and decreasing right frontal activity. Similarly we were interested in deciphering whether the negative lateral frontal asymmetry values observed in the *mild pleasure* group were driven by (a) increasing right frontal activity, (b) decreasing left frontal activity, or (c) decreasing left frontal activity and increasing right frontal activity. We found that increasing left lateral frontal activity accounted for the changes in the *intense pleasure* group ($r = -.29$ vs. $r = -.03$, $p < .05$). We found that the combination of decreasing left frontal and increasing right frontal activity accounted for the asymmetry in the *mild*

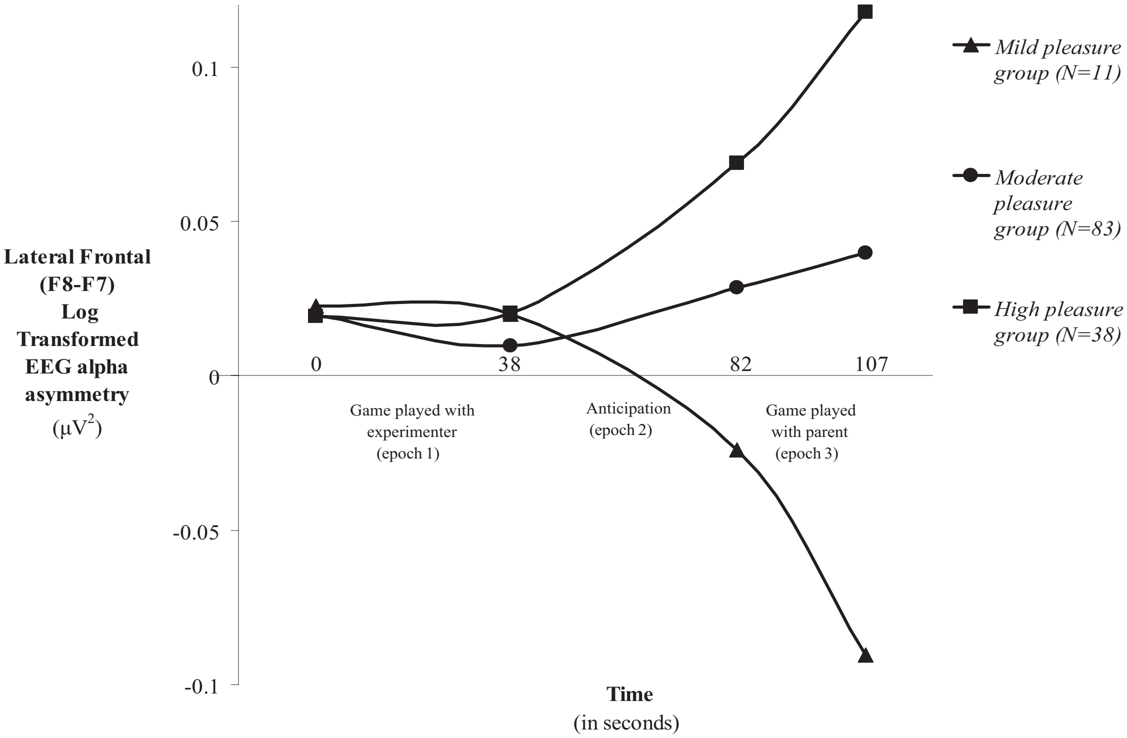

Figure 2. Lateral frontal EEG asymmetry trajectories during the “pop-out toy” task for the *mild*, *moderate*, and *intense pleasure* groups. The first data point on the graph represents where each group’s lateral frontal EEG asymmetry score was at the beginning of “game played with experimenter.” The last three data points represent where each group’s EEG asymmetry score was at the end of “game played with experimenter,” “anticipation,” and “game played with parent,” respectively.

pleasure group ($r = .35$ vs. $r = .03$; *ns*), and the combination of increasing left and decreasing right frontal activity accounted for the observed asymmetry in the *moderate pleasure* group ($r = -.12$ vs. $r = -.08$, *ns*).

Is the Relationship Between Change in Lateral Frontal EEG Asymmetry and Pleasure Unique to the Frontal Region?

The Level-1 and Level-2 models that were combined and applied to the lateral frontal EEG asymmetry data were also applied to the parietal EEG asymmetry data. The significant predictive effects that were present in the lateral frontal model were absent when this model was applied to the parietal EEG data (all ps $>$ .70). This result suggests that the observed relationship between pleasure and task-dependent change in lateral frontal EEG asymmetry during a positive stimulus is unique to the frontal region and does not reflect whole-brain changes.

Furthermore, we conducted an additional analysis to determine whether the shift in lateral frontal asymmetry observed during the task was significantly stronger than any shift in parietal asymmetry. To this end, we computed a "change" score by subtracting each child's lateral frontal EEG asymmetry score and parietal asymmetry score at the onset of "game played with experimenter" from his or her lateral frontal EEG asymmetry score or parietal EEG asymmetry score at the end of "game played with parent." We then used a repeated-measures ANOVA that included all children in the sample to determine whether the change in asymmetry score differed by region; we found that it did. The average amount of change in lateral frontal EEG asymmetry from onset to offset of the task was .03 (*SEM* = .007), whereas the average change in parietal EEG asymmetry from onset to offset of the task was 0 (*SEM* = .005). The degree of change in the two regions was significantly different ($p < .001$), indicating that the dynamic change in asymmetry score was stronger in the lateral frontal region relative to the parietal region.

Discussion

The results from this study suggest that the second-by-second changes in the expression of pleasure during a positive stimulus is related to dynamic growth in left lateral frontal activation over the course of the task. Baseline lateral frontal EEG asymmetry (a traitlike marker) did not relate to the amount of pleasure expressed during the "pop-out toy" task. We predicted that it would be related to pleasure during this task. It may be that responses to this task are more situational or state governed rather than reflecting more traitlike variation associated with individual differences in baseline frontal asymmetry.

Increasing left lateral frontal activity during a positive stimulus was predicted by the amount of pleasure displayed. Previous research involving children supports the idea that left lateral frontal activity is related to positive emotion (Davidson & Fox, 1982; Fox & Davidson, 1986). The present data suggest that the dynamic nonlinear growth in the second-by-second sequence of lateral frontal EEG asymmetry tracks the chronometry of task-dependent pleasure. These findings indicate that an important component of individual differences in affective style (Davidson, 2000) is the dynamic unfolding of pleasure over time. Those children whose expression of pleasure accelerates more rapidly show greater growth in relative left lateral frontal activation as the task evolves. The data underscore the utility of harnessing the temporal information in the EEG to characterize individual differences in affective chronometry.

The task we studied in this report provided an excellent basis for examining how pleasure does and does not build up as a result of contact with pleasure-inducing stimuli. This feature of the task may be a key reason for the changes in activation observed in this frontal region as the task evolved. The increasing left lateral frontal activation observed in a subset of the children tested may be an indication that this region plays a role in the propagation of an increasingly intense positive emotional state over time, whereas the combination of decreasing left/increasing right lateral frontal activation over time may mark the propagation of a less intense, calm positive emotional state—likely characterized by contentment or some variant of it—over time. The propagation of an intense or calm positive emotional state over the course of a task may be conceptualized as a form of affective working memory (Davidson, 2004b; Pizzagalli, Sherwood, Henriques, & Davidson, 2005) because it seems likely that humans possess a neurophysiological mechanism for making positive emotional states last as long as possible. Our findings are consistent with the notion that the frontal cortex supports this form of affective working memory, and, more specifically, the data indicate that accelerating growth in left prefrontal activation is associated with a pattern of growing pleasure as the task develops. In contrast, those children whose expression of pleasure remains moderate and unchanging tend to exhibit both increasing left and decreasing right lateral frontal activation as the task develops. In contrast, those children whose expression of pleasure remains relatively mild and unchanging across the task are characterized by a pattern of combined decreasing left and increasing right lateral frontal activation as the task unfolds. We believe that the decreasing left frontal activity/ increasing right frontal activity observed in the *mild pleasure* group may signal that these children experienced a nonapproach-oriented form of positive emotion such as contentment during the task. This formulation fits with the approach–withdrawal model of lateral frontal EEG asymmetry—and highlights the need to consider the internally focused versus externally focused facet of the approach–withdrawal spectrum—because the combination of increasing right frontal activity and decreasing left frontal activity may relate to internally focused, self-reflective positively valenced emotions such as contentment, just as left frontal activity has been found to relate to externally focused, approach-related negative emotions such as anger (Harmon-Jones, 2003).

The differences in frontal brain activation observed during this novel, positive-affect-eliciting task suggest that individual children differ in the degree to which they become engaged by highly active forms of positive emotion (e.g., joy) versus calmer forms of positive emotion (e.g., contentment) in the moment. If the concept of positive affect is partitioned in a similar manner as negative affective states have been, then one can ask the question: How might different positive emotional states be differentiated neurophysiologically? Our data suggest that individual differences in the way one child versus another manifests positive affect in response to the same stimulus may be linked to differences in his or her frontal brain activity during the task. Further study will be necessary to determine whether this state effect may relate to a more long-term, traitlike tendency to engage in high-intensity forms of positive emotion or calm forms of positive emotion on a regular basis (i.e., individual children may tend to fall on one end of a positive affect continuum or the other, tending to routinely express exuberance rather than contentment—or vice versa—in response to positive stimuli). Whether the state effects observed in the present study map onto trait differences should be investigated empirically.

It will be interesting to determine whether individual differences in positive emotional tendencies relate to different social, cognitive, emotional, or educational/vocational outcomes. For example, Masters, Barden, and Ford (1979) found that 4-year-old children who were asked to either spend 30 s remembering "something that happened that made you feel so happy you just wanted to jump up and down" (p. 382)—a condition designed to elicit exuberance—or spend 30 s remembering "something that happened that made you feel so happy that you just wanted to sit and smile" (p. 382)—a condition designed to induce contentment—engaged in more efficient problem solving than did children who were not asked to think about a happy moment. Importantly, both the contentment and happiness conditions led to statistically even elevations in problem-solving ability relative to the control condition. This result suggests that children's experience of different types of positive affect in certain contexts may lead to similar outcomes. However, it is also likely that children differ in their propensity to experience different types of positive affect, and more refined analyses may reveal different effects of contentment and exuberance. Our findings underscore the critical need to dissect the neural underpinnings of these different forms of positive affect. As it happens, we may come to find that eliciting/increasing contentment has distinct positive effects relative to eliciting/increasing happiness, and designing methods to elicit contentment may be a useful tool for promoting learning and general well-being in certain children, whereas eliciting/increasing happiness may be more useful for promoting learning and well-being in other children.

It is important to note that the scalp-recorded EEG is a coarse reflection of integrated regional brain activity, and thus the localization of the underlying sources of the scalp-recorded signals is approximate at best. However, the virtue of these measures lies in their temporal resolution, which is on the same time scale as the dynamic changes in pleasure that can be reliably coded from the behavior of children. Our findings show that the dynamic time course of these prefrontal electrical changes may reflect important features of individual variation in affective chronometry. The fact that our findings are derived from children in the 6–10-year age range is noteworthy. Children of this age show rich expression of affect, which tends to be more constrained and socially managed in adults. Thus, in addition to their intrinsic worth in illustrating early manifestations of affective style and temperament, the use of children to study the brain electrical changes that dynamically vary with affect may be particularly significant since overt, reliably coded behavioral expressions of pleasure can easily be quantified in subjects this age.

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Received July 11, 2007
Revision received September 8, 2008
Accepted September 16, 2008 ■