

The Blur of Pleasure: Appetitively Appealing Stimuli Decrease Subjective Temporal Perceptual Acuity

Kevin H. Roberts, Grace Truong, Alan Kingstone,
and Rebecca M. Todd

Department of Psychology, University of British Columbia

Psychological Science

1–20

© The Author(s) 2017

Reprints and permissions:

sagepub.com/journalsPermissions.nav

DOI: 10.1177/0956797617702698

www.psychologicalscience.org/PS



Abstract

Anecdotal reports that time “flies by” or “slows down” during emotional events are supported by evidence that the motivational relevance of stimuli influences subsequent duration judgments. Yet it is unknown whether the subjective quality of events as they unfold is altered by motivational relevance. In a novel paradigm, we measured the subjective experience of moment-to-moment visual perception. Participants judged the temporal smoothness of high-approach positive images (desserts), negative images (e.g., of bodily mutilation), and neutral images (commonplace scenes) as they faded to black. Results revealed approach-motivated blurring, such that positive stimuli were judged as smoother and negative stimuli as choppy relative to neutral stimuli. Participants’ ratings of approach motivation predicted perceived fade smoothness after we controlled for low-level stimulus features. Electrophysiological data indicated that approach-motivated blurring modulated relatively rapid perceptual activation. These results indicate that stimulus value influences subjective temporal perceptual acuity; approach-motivating stimuli elicit perception of a “blurred” frame rate characteristic of speeded motion.

Keywords

time perception, motivation, emotions, visual perception

Received 12/1/15; Revision accepted 3/13/17

Subjective time distortions are commonplace in everyday life. People often speak of time as dragging or flying, attributing such distortions to their affective state or features of the environment. Empirically, extensive evidence indicates that negative stimuli that elicit a defensive response (e.g., angry faces, pictures of bodily injuries) are judged as lasting longer than neutral stimuli (Dirnberger et al., 2012; Droit-Volet, Brunot, & Niedenthal, 2004). Effects of positive stimuli are more mixed. Although some types of positive stimuli have been found to produce overestimation of stimulus duration (Lambrechts, Mella, Pouthas, & Noulhiane, 2011; Noulhiane, Mella, Samson, Ragot, & Pouthas, 2007), appetitive stimuli (e.g., delicious desserts) have been linked to underestimation of duration if they are highly approach motivating (Gable & Poole, 2012). It has been suggested that subjective time perception is an index of the direction of the action tendency elicited by a

stimulus (Angrilli, Cherubini, Pavese, & Mantredini, 1997). Yet the mixed results for positive stimuli highlight the need for a better understanding of the mechanisms underlying affective influences on the perception of time.

Emotionally salient stimuli have also been associated with an altered experience of visual perception (Phelps, Ling, & Carrasco, 2006; Todd, Talmi, Schmitz, Susskind, & Anderson, 2012). In previous studies, we employed a psychophysical magnitude-estimation task to examine effects of emotional salience on perceptual experience and found that viewing arousing emotional stimuli increased the experience of perceptual vividness or

Corresponding Author:

Kevin H. Roberts, Department of Psychology, University of British Columbia, 2136 West Mall, Vancouver, British Columbia V6T 1Z4, Canada
E-mail: kevin.roberts@psych.ubc.ca

enhanced the signal-to-noise ratio associated with relatively rapid perceptual processing (Todd et al., 2015; Todd et al., 2012). One potential explanation for this latter effect is that it results from increased temporal sampling of emotionally salient images, and thus should be associated with altered time perception. Supporting this proposal, models emerging from research with non-human animals have linked effects of motivation to neurobiological mechanisms of timekeeping (Matell & Meck, 2004; Meck, 1996). Such models posit that subjective time estimation is regulated by an internal pacemaker that operates via striatal timekeeping mechanisms.

In the present study, we adopted a similar psychophysical magnitude-estimation approach to examine effects of valence on the moment-to-moment experience of visual perception within a framework proposed by pacemaker models. We created a novel paradigm in which stimuli faded to black over the course of 2 s, and detection of changes from frame to frame served to index perception during pacemaker “pulses.” We assumed that the images used in the study would result in differences in the clock speed of a neural pacemaker (Matell & Meck, 2004). Given this premise, we hypothesized that differences in pacemaker speed would result in differences in subjective perception of a continuous stimulus, such that increased pacemaker speed would be associated with increased perceptual sampling rate, and thus increased temporal acuity. Thus, we used judgments of the smoothness or choppieness of a fading stimulus as an index of subjective temporal acuity. Specifically, an increase in temporal acuity would increase ability to discern fine-grained changes across time in the stimulus fade and therefore would lead to subjective ratings of choppieness. Conversely, a reduction in temporal acuity would reduce ability to discern frame-to-frame changes in the stimulus and therefore would lead to subjective ratings of smoothness. Thus, we predicted that stimuli eliciting high approach motivation would result in the fade being experienced as smoother (because of reduced subjective acuity associated with a speeded sense of time) and that stimuli eliciting avoidance would result in the fade being experienced as choppiest (because of increased subjective acuity associated with an extended sense of time). In addition, we predicted that, trial by trial, stimuli rated as higher in approach motivation would elicit greater estimations of smoothness. Moreover, we expected that effects of approach motivation on subjective smoothness would reflect subjective influences on perceptual processing.

Experiment 1

Method

Participants. Thirty-two university undergraduates (23 female, 9 male; mean age = 20.2 years, $SD = 2.22$) with

normal or corrected-to-normal vision participated for course credit. The experimental protocol was approved by the University of British Columbia Behavioural Research Ethics Board and was in accordance with the World Medical Association Declaration of Helsinki. The required number of participants was estimated to be approximately 30, based on previous experiments using a magnitude-estimation method to probe the subjective experience of affective stimuli (Todd et al., 2012). Data collection was stopped when approximately the targeted number of participants was reached. Four participants were excluded because of testing error, and 1 participant was excluded because of software malfunction. An additional 4 participants were excluded for rating neutral stimuli presented at 16 frames per second (fps; the objectively choppiest display rate) as more smooth, on average, than neutral stimuli presented at 48 fps (the objectively smoothest display rate), as this indicated that they had either flat or inverted response curves and did not properly perform the basic perceptual task of discriminating choppiest from smoother fades. These participants could not be used in our inferential analyses because any influence of affect on smoothness ratings would be confounded by their inability to perform the task. Data from 23 participants (15 female, 8 male; mean age = 20.3 years, $SD = 2.39$) were included in our analyses.

Materials. Equal numbers of negative, neutral, and positive images were used as target stimuli (75 images in total). The negative and neutral images were retrieved from the International Affective Picture System (Lang, Bradley, & Cuthbert, 2008), and the positive images were retrieved from the Internet. The negative stimuli depicted scenes of mutilation, death, and confrontation; the neutral stimuli depicted commonplace scenes (e.g., grocery store, parking lot); and the positive stimuli were images of deserts selected to elicit approach motivation (Gable & Poole, 2012). The three stimulus categories were matched in mean log luminance and contrast. Other objective stimulus characteristics were controlled for statistically. A mosaic-like, spatially scrambled version of each target stimulus was created to act as its standard comparison stimulus. Both standard and target stimuli subtended a visual angle of approximately $8.97^\circ \times 6.76^\circ$. All tasks were performed on a BenQ XL2420Z monitor (Taipei, Taiwan) with a resolution of $1,280 \times 1,024$ pixels and a refresh rate of 144 Hz.

Procedure. In each of the 225 trials of the magnitude-estimation task, participants judged the relative smoothness of a target stimulus fading to black, as compared with the corresponding standard stimulus fading to black (Fig. 1). Each trial began with a fixation cross lasting 1,000 ms. It was followed by a standard stimulus that was presented for 2,000 ms, fading to black at a rate of 24 fps. Immediately following the standard, the target stimulus

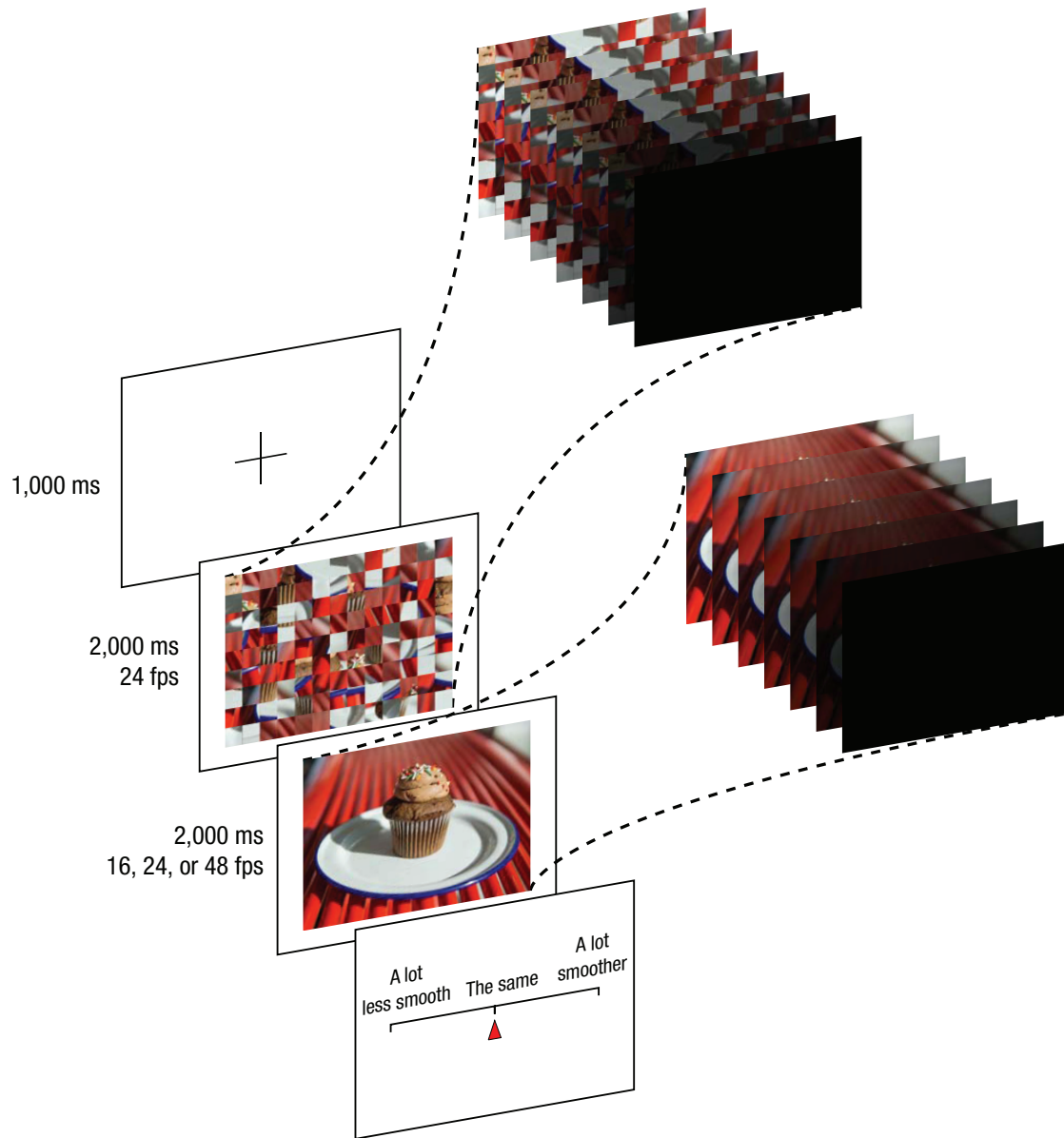


Fig. 1. Illustration of the magnitude-estimation task employed in Experiment 1 and Experiment 2. Following the presentation of a fixation cross, a comparison stimulus and then the corresponding target stimulus were presented; each stimulus faded to black over 2,000 ms, and the frame rate of the target's fade was manipulated across trials. Participants' task was to judge the fade smoothness of the target relative to the comparison. Note that in Experiment 2, the anchors on the rating scale were *a lot less continuous* and *a lot more continuous*. fps = frames per second.

was displayed for 2,000 ms, fading to black at one of three possible frame rates (16, 24, or 48 fps); a lower frame rate resulted in fewer frames across the 2,000-ms period, and consequently a longer duration for each individual frame of the fade, as well as more noticeable frame-to-frame changes in stimulus luminance (and thus a “choppier” percept across time). Depending on the frame rate, the 2,000-ms fade animation was shown in 32, 48, or 96 frames, with each frame presented for 62.5 ms, 41.7 ms, or 20.8 ms, respectively. After viewing the target fading, participants indicated its fade smoothness compared with the standard, on a 21-point scale from -11, *a*

lot less smooth (i.e., a choppy fade), at the left to 11, *a lot smoother* (i.e., a smooth fade), at the right; the midpoint of the scale was labeled *the same*. Trial order was pseudorandomized, and each target image was presented at each frame rate once. Six practice trials were completed prior to the experimental trials so that participants could become accustomed to the task.

After completing the magnitude-estimation task, participants rated each image for emotional arousal on a scale from 1 (low arousal, “completely relaxed, calm, sluggish, or dull”) to 7 (high arousal, “excited, jittery, or wide awake”). The instructions noted that this was

Table 1. Descriptive Statistics for the Image Ratings and Participants' Responses for When They Last Ate

Variable	Experiment 1	Experiment 2	Experiment 3
Approach/avoidance ratings			
Negative stimuli	6.74 (2.74)	6.56 (3.11)	5.16 (2.94)
Neutral stimuli	10.74 (0.73)	10.54 (1.44)	10.91 (1.02)
Positive stimuli	13.8 (2.13)	14.35 (2.66)	15.12 (2.51)
Arousal ratings			
Negative stimuli	4.71 (1.28)	5.03 (1.60)	5.67 (1.00)
Neutral stimuli	1.84 (0.65)	2.11 (0.66)	1.84 (0.51)
Positive stimuli	3.49 (1.47)	3.98 (1.63)	3.43 (1.33)
Time since eating (minutes)	195.74 (271.32)	290.58 (263.65)	259.94 (304.80)

Note: The table presents means, with standard deviations in parentheses.

not a rating of pleasantness, as arousal can be both positive (excitement) or negative (upset, anxiety). On a separate 21-point scale, participants also rated the degree to which each image elicited an avoidance or approach motivation toward the subject or scene of the stimulus; 1 indicated high avoidance and 21 indicated high approach. During these rating tasks, all images were presented for 2,000 ms without fading to black. Participants completed six practice trials of each rating task prior to the experimental trials. Finally, because hunger might influence approach motivation toward pictures of desserts, we asked participants how long it had been since they had last eaten.

In order to assess and control for the effect of objective stimulus properties on perceived fade smoothness, we calculated the degree of edges, contrast, and saturation in each image using the Image Processing Toolbox packaged with MATLAB 8.3.0 (The MathWorks, Natick, MA). Degree of edges was calculated with MATLAB's edge function, using a Canny filter with a threshold of 0.5. Contrast was calculated by finding the standard deviation of the gray-scale pixel values. Saturation was calculated by extracting the mean value of each image's saturation dimension after the image was converted to a hue-saturation-value (HSV) color map using MATLAB's rgb2hsv function.

Results

For all analyses, reported values are Greenhouse-Geisser corrected when sphericity cannot be assumed, and pairwise comparisons are Bonferroni corrected.

Stimulus ratings. Arousal and approach/avoidance ratings of the stimuli (Table 1) were submitted to one-way repeated measures analyses of variance (ANOVAs) to verify differences among the stimulus categories. For arousal ratings, there was a main effect of stimulus

category, $F(2, 44) = 39.20, p < .001, \eta_p^2 = .64$. Pairwise comparisons revealed that negative stimuli were rated as significantly more arousing than neutral ($p < .001$) and positive ($p = .016$) stimuli, and positive stimuli were rated as significantly more arousing than neutral stimuli ($p < .001$). For ratings of approach/avoidance, there was also a main effect of stimulus category, $F(1.52, 33.53) = 64.33, p < .001, \eta_p^2 = .75$. Pairwise comparisons revealed that negative images were rated as more avoidance motivating and positive stimuli were rated as more approach motivating compared with neutral images (both $ps < .001$). Together, these results confirmed that our stimuli elicited the expected pattern of differential arousal and approach motivation. Time since eating (Table 1) was not significantly correlated with arousal or approach/avoidance ratings for positive stimuli, $ps > .250$.

Perceived fade smoothness. A 3 (stimulus frame rate) \times 3 (stimulus category) repeated measures ANOVA was performed on the data for perceived fade smoothness of the target (Fig. 2a). There was a main effect of stimulus frame rate, $F(1.13, 24.90) = 35.16, p < .001, \eta_p^2 = .62$, observed power = 1.00. Pairwise comparisons revealed significantly different perceived fade smoothness across all levels ($ps \leq .001$); higher stimulus frame rate was associated with higher perceived fade smoothness. A main effect of stimulus category was also obtained, $F(1.32, 28.95) = 9.06, p = .003, \eta_p^2 = .29$, observed power = .892; negative stimuli were rated as least smooth, and positive stimuli were rated as smoothest (Table 2). Pairwise comparisons revealed significant differences between positive and neutral stimuli ($p = .007$) and between positive and negative stimuli ($p = .012$), but no significant difference between neutral and negative stimuli ($p = .242$). Thus, positive images were rated as smoother than negative and neutral pictures. There was also a significant interaction between the two factors, $F(4, 88) = 5.21, p = .001, \eta_p^2 = .19$. Simple-effects analyses revealed a difference between

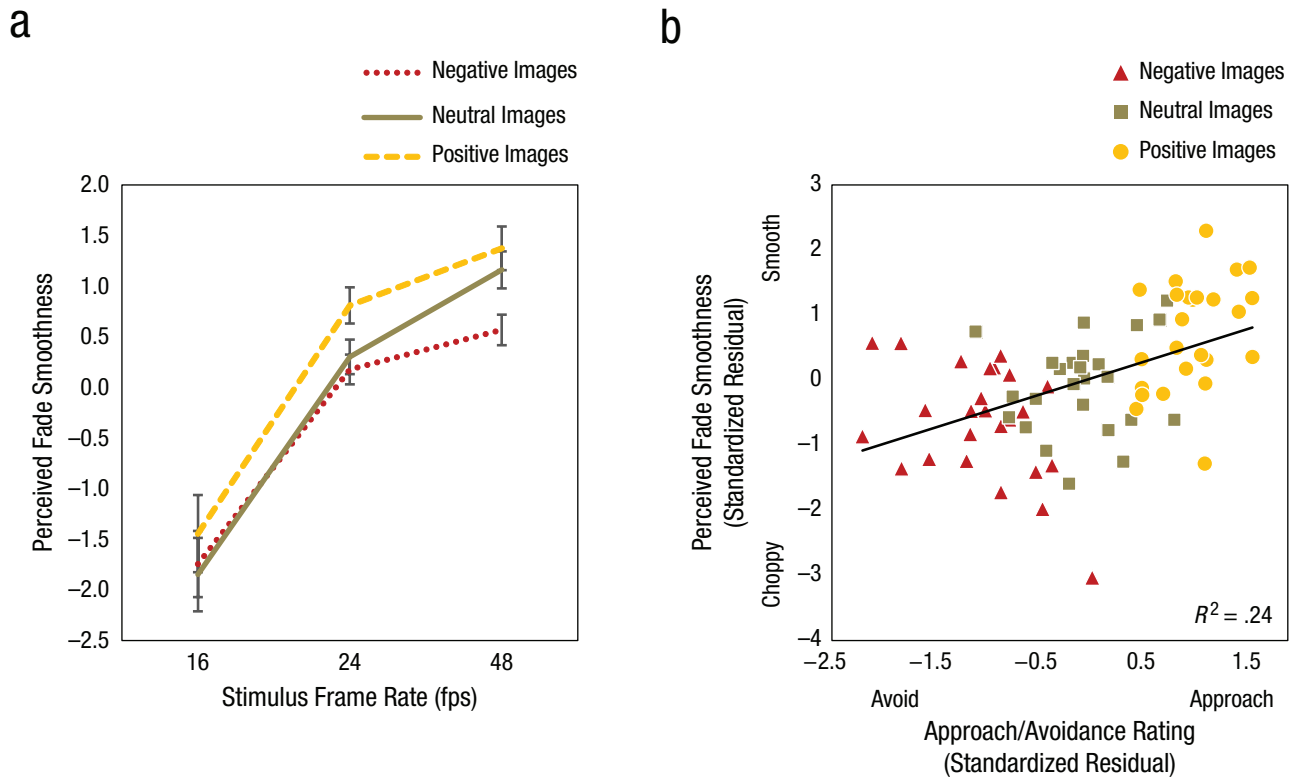


Fig. 2. Affective influences on perceived fade smoothness of the target in Experiment 1. The line graph (a) shows perceived fade smoothness as a function of stimulus frame rate (fps = frames per second), separately for the three stimulus categories. Error bars indicate ± 1 SEM. The scatterplot (b) shows the relation between the standardized residuals of mean approach/avoidance ratings and perceived fade smoothness after controlling for low-level objective stimulus properties. Each plotted point represents results for a single stimulus, across participants; the category of the stimulus is indicated by the symbol (triangle, square, or circle). Also shown is the best-fitting regression line.

positive and neutral images in the 16-fps condition ($p = .035$), differences between positive and neutral and between positive and negative images in the 24-fps condition ($p = .009, p = .004$), and differences between positive

and negative and between negative and neutral images in the 48-fps condition ($p = .002, p = .001$); all other comparisons were nonsignificant ($ps > .250$). Thus, positive images were smoother than neutral but not negative

Table 2. Perceived Fade Smoothness for Each Stimulus Category and Frame Rate

Experiment and stimulus category	Manipulated frame rate					
	16 fps		24 fps		48 fps	
	Mean	95% CI	Mean	95% CI	Mean	95% CI
Experiment 1						
Negative	-1.74 (1.57)	[-2.42, -1.07]	0.18 (0.71)	[-0.13, 0.48]	0.57 (0.72)	[0.26, 0.88]
Neutral	-1.85 (1.74)	[-2.60, -1.09]	0.30 (0.81)	[-0.05, 0.65]	1.16 (0.87)	[0.78, 1.54]
Positive	-1.44 (1.83)	[-2.23, -0.65]	0.81 (0.86)	[0.44, 1.18]	1.37 (1.04)	[0.93, 1.82]
Experiment 2						
Negative	-0.99 (1.41)	[-1.59, -0.39]	0.00 (0.70)	[-0.30, 0.29]	0.21 (0.88)	[-0.17, 0.58]
Neutral	-0.85 (1.19)	[-1.36, -0.35]	0.46 (0.64)	[0.19, 0.73]	0.74 (0.72)	[0.43, 1.04]
Positive	-0.49 (1.44)	[-1.09, 0.12]	0.82 (1.06)	[0.37, 1.27]	0.93 (1.00)	[0.51, 1.35]
Experiment 3						
Negative	1.82 (1.99)	[0.86, 2.78]	0.25 (0.85)	[-0.16, 0.66]	-0.02 (0.88)	[-0.44, 0.41]
Neutral	2.03 (1.06)	[1.52, 2.54]	0.51 (0.97)	[0.05, 0.98]	0.33 (1.03)	[-0.17, 0.82]
Positive	2.83 (1.94)	[1.90, 3.76]	1.22 (1.36)	[0.57, 1.88]	0.95 (1.31)	[0.31, 1.58]

Note: Values in parentheses are standard deviations. fps = frames per second; CI = confidence interval.

images at the lowest frame rate, were smoother than both neutral and negative images at the medium frame rate, and were smoother than only negative images at the highest frame rate. Negative images were rated as choppy than neutral images only at the highest frame rate. Thus, negative images were rated as choppiest and positive images as smoothest overall, which suggests reduced subjective temporal acuity for more positive stimuli, and this pattern was most strongly driven by perceived fade smoothness for positive images.

Stimulus ratings predicting perceived fade smoothness. We employed a multilevel model using the `lme4` package for R (Bates, Maechler, Bolker, & Walker, 2014; R Core Team, 2014) to look at the trial-by-trial within-subjects effect of image ratings on perceived fade smoothness after controlling for other potential influences (time since the participant last ate; degree of edges, contrast, and saturation in the target stimulus). Results showed that the degree of edges in an image significantly influenced perceived fade smoothness, $\beta = -0.10$, $t(69.93) = -3.56$, $p < .001$; more edges in an image resulted in perception of the fade as less smooth. Stimulus contrast also significantly influenced perceived fade smoothness, $\beta = -0.05$, $t(71.48) = -2.01$, $p = .048$; more contrast resulted in perception of a less smooth fade. As predicted, when we controlled for the effect of all other variables in the model, approach/avoidance ratings were significantly related to perceived fade smoothness, $\beta = 0.15$, $t(19.63) = 2.77$, $p = .012$; higher approach ratings resulted in perception of smoother fading (Fig. 2b). This effect was also significant when arousal, time since eating, and objective stimulus characteristics were not included in the model, $\beta = 0.15$, $t(23.97) = 2.83$, $p = .009$. Perceived fade smoothness was not related to saturation, arousal ratings, or time since eating ($ps > .250$). Thus, a multiple-level analysis showed that stimuli eliciting a higher level of approach motivation were perceived to fade more smoothly. This result is consistent with the proposal that approach motivation is associated with speeded time perception and reduced rates of sampling.

Experiment 2

Method

The results from Experiment 1 indicated that the motivational relevance of images affects the subjective moment-to-moment perceptual experience of stimuli. However, it was possible that the pattern of results obtained was due to the implicit affective connotation of the words used in the magnitude-estimation task. The word *smooth* may have a positive connotation that was transferred into a bias toward estimating positive

images as more smooth and negative images as less smooth. Further, we described the opposing temporal perceptual experience as “choppy,” which may have a negative connotation, which could have further influenced participants to rate negative images as less smooth. To control for this confound, we performed a nearly identical experiment, in which the only change was to use the word *continuous* to describe a smooth fade and the word *discrete* to describe a choppy fade.

Participants. Thirty-eight university undergraduates (21 female, 17 male; mean age = 20.7 years, $SD = 2.83$) with normal or corrected-to-normal vision participated for course credit. The experimental protocol was approved by the University of British Columbia Behavioural Research Ethics Board and was in accordance with the World Medical Association Declaration of Helsinki. As in Experiment 1, the required number of participants was estimated to be approximately 30, based on previous similar experiments (Todd et al., 2012). Data collection was stopped when approximately the targeted number of participants was reached. One participant withdrew from the experiment. An additional 13 participants were excluded for rating neutral stimuli presented at 16 fps as more smooth, on average, than neutral stimuli presented at 48 fps, as this indicated that they had either flat or inverted response curves and did not properly perform the basic perceptual task of discriminating choppy from smoother fades. Data from the remaining 24 participants (12 female, 12 male; mean age = 20.7 years, $SD = 3.31$) were included in analyses.

Materials and procedure. The stimuli, display parameters, and procedure were identical to those in Experiment 1, except that the words *smooth* and *choppy* were replaced by *continuous* and *discrete*, respectively, in all oral and written instructions given to the participants. Thus, the labels at the opposing ends of the rating scale in the magnitude-estimation task were *a lot less continuous* and *a lot more continuous*.

Results

For all analyses, reported values are Greenhouse-Geisser corrected when sphericity cannot be assumed, and pairwise comparisons are Bonferroni corrected.

Stimulus ratings. Arousal and approach/avoidance ratings of the stimuli (Table 1) were submitted to one-way repeated measures ANOVAs, which resulted in the same pattern of results as in Experiment 1, with the exception that although negative stimuli were rated as more arousing than positive stimuli, this difference was not significant ($p = .09$; for details, see the Supplemental

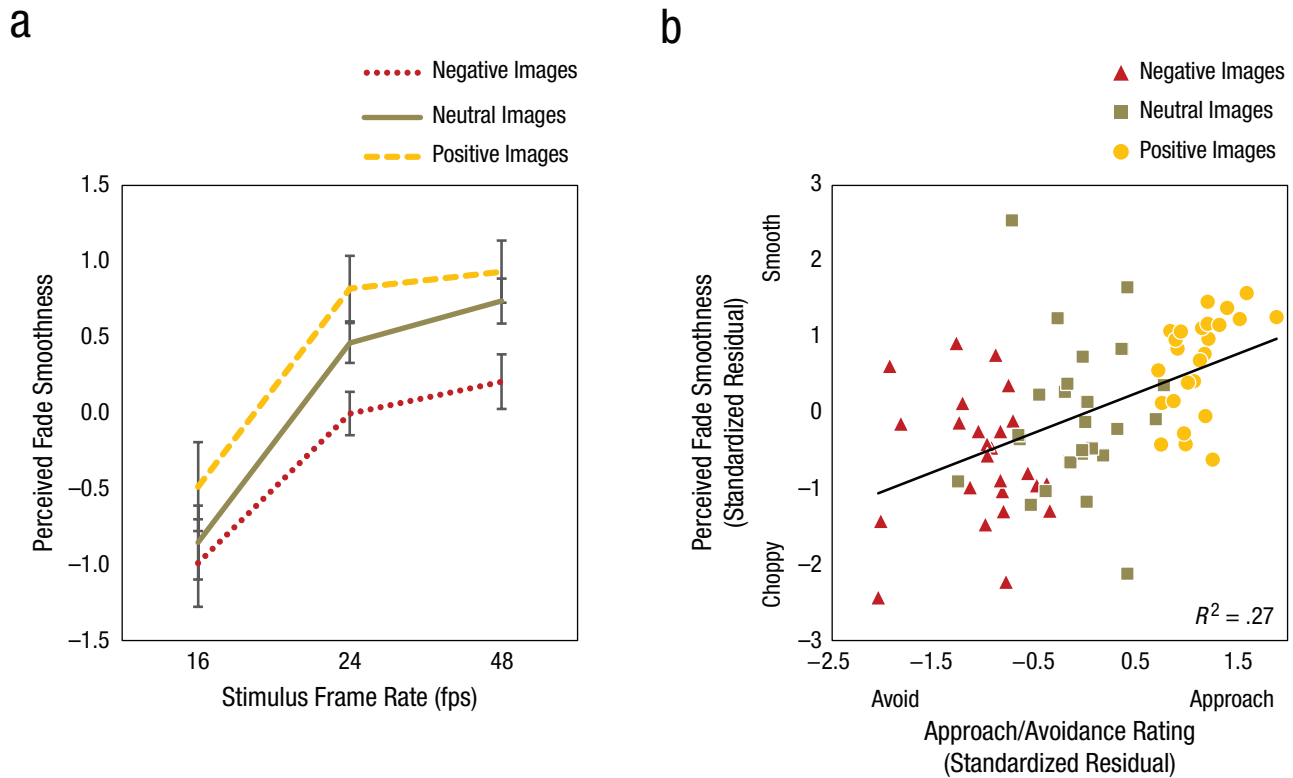


Fig. 3. Affective influences on perceived fade smoothness of the target in Experiment 2. The line graph (a) shows perceived fade smoothness as a function of stimulus frame rate (fps = frames per second), separately for the three stimulus categories. Error bars indicate ± 1 SEM. The scatterplot (b) shows the relation between the standardized residuals of mean approach/avoidance ratings and perceived fade smoothness after controlling for low-level objective stimulus properties. Each plotted point represents results for a single stimulus, across participants; the category of the stimulus is indicated by the symbol (triangle, square, or circle). Also shown is the best-fitting regression line.

Material available online). Time since eating (Table 1) was not significantly correlated with arousal or approach/avoidance ratings for positive stimuli, $p_s > .250$.

Perceived fade smoothness. A 3 (stimulus frame rate) \times 3 (stimulus category) repeated measures ANOVA was performed on the data for perceived fade smoothness of the target (Fig. 3a). There was a main effect of stimulus frame rate, $F(1.13, 25.90) = 16.71$, $p < .001$, $\eta_p^2 = .42$, observed power = .984. Pairwise comparisons revealed significantly different perceived fade smoothness between the 16-fps condition and both the 24-fps condition and the 48-fps condition ($p_s = .001$); higher stimulus frame rate resulted in higher perceived fade smoothness. There was no significant difference between the 24-fps and 48-fps conditions ($p > .250$). A main effect of stimulus category was also obtained, $F(1.46, 33.67) = 10.26$, $p = .001$, $\eta_p^2 = .31$, observed power = .945; negative stimuli were rated as least smooth, and positive stimuli were rated as smoothest (Table 2). Pairwise comparisons revealed significant differences between positive stimuli and both neutral stimuli ($p = .038$) and negative stimuli

($p = .005$) and a significant difference between neutral and negative stimuli ($p = .039$). Thus, positive stimuli were rated as smoother and negative stimuli as less smooth than neutral stimuli. There was no significant interaction between the two factors, $F(4, 92) = 1.91$, $p = .116$, $\eta_p^2 = .08$. In summary, negative images were rated as choppiest and positive images as smoothest, which suggests that subjective temporal acuity was reduced for positive stimuli and increased for negative stimuli.

Stimulus ratings predicting perceived fade smoothness. The same multilevel model used in Experiment 1 was employed to investigate the effect of image ratings on perceived fade smoothness, controlling for time since the participant last ate and objective stimulus properties. Results showed that stimulus contrast significantly influenced perceived fade smoothness, $\beta = -0.13$, $t(67.97) = -4.38$, $p < .001$; higher contrast in an image resulted in perception of a less smooth fade. As predicted, when we controlled for the effect of all other variables in the model, approach/avoidance ratings were significantly related to perceived fade smoothness, $\beta = 0.08$, $t(18.04) = 2.18$,

$p = .043$; higher approach ratings resulted in perception of smoother fading (Fig. 3b), though this effect was not significant when arousal, time since eating, and objective stimulus characteristics were not included in the model, $\beta = 0.09$, $t(19.94) = 1.94$, $p = .067$. Perceived fade smoothness was not related to degree of edges, saturation, arousal ratings, or time since eating ($ps > .250$). Thus, a multiple-level analysis showed that stimuli eliciting a higher level of approach motivation were perceived to fade more smoothly. This result is consistent with the proposal that approach motivation is associated with speeded time perception and reduced rates of sampling.

Experiment 3

Method

The results from Experiment 2 indicated that the results we obtained in Experiment 1 were not due to the implicit affective connotation of the words used in the materials participants received (i.e., *smooth* and *choppy*). Next, we employed electroencephalography (EEG) to further probe the observed effect, which we term *approach-motivated blurring* (AMB). In Experiment 3, we aimed to use event-related potentials (ERPs) to probe differences in scalp potentials reflecting variation in perceived stimulus smoothness related to the influence of approach motivation. Specifically, if early-latency ERPs were parametrically modulated by subjective ratings reflecting AMB, this would provide evidence that the affective modulation of subjective smoothness ratings observed in the previous experiments reflects subjective enhancement of perceptual processing. Moreover, modulation of the occipital late positive potential (LPP) would further link our results to previous findings of enhanced sustained processing of emotionally and motivationally salient stimuli. The AMB effect indicates that subjective smoothness is highly associated with the motivational content of picture stimuli, and the LPP is modulated by the affective content of picture stimuli (Cuthbert, Schupp, Bradley, Birbaumer, & Lang, 2000). Thus, the LPP should be modulated by AMB. However, because valence-related effects diverge for different categories of positive stimuli, we could not predict the direction of AMB-related ERP modulation on the basis of previous research.

Participants. Thirty-one university undergraduates (25 female, 6 male; mean age = 21.6 years, $SD = 2.87$) with normal or corrected-to-normal vision participated for course credit. The experimental protocol was approved by the University of British Columbia Behavioural Research Ethics Board and was in accordance with the World Medical Association Declaration of Helsinki. The required

number of participants was estimated to be approximately 30, based on previous similar experiments investigating ERP responses to affective stimuli (Todd et al., 2012). Data collection was stopped when approximately the targeted number of participants was reached. Six participants were excluded for rating stimuli presented at 16 fps as more smooth, on average, than stimuli presented at 48 fps, across all stimulus categories, as this indicated that they had either flat or inverted response curves and did not properly perform the basic perceptual task of discriminating choppy from smoother fades. An additional 6 participants were excluded from analyses for having too few trials remaining after our EEG artifact-rejection procedure. Data from the remaining 19 participants (18 female, 1 male; mean age = 21.8 years, $SD = 3.30$) were included in analyses. One participant had missing data for time since last eating and was excluded only for analyses that required this variable.

Materials and procedure. The stimuli and display parameters were identical to those in Experiment 1. The procedure was similar to that of Experiment 1, with a slight alteration to the magnitude-estimation task. Instead of varying the frame rate of the target, in this experiment we varied the frame rate of the standard image. This was done to ensure that the main ERP of interest (the response to the target image) reflected perceived rather than actual differences in the smoothness of the target stimulus. After the standard was displayed, a fixation cross of variable duration (500–900 ms, uniformly randomized) was presented. It was immediately followed by the target image, which was presented for 2,000 ms at 24 fps.

EEG recording and analysis. Scalp potentials were recorded continuously at a sampling rate of 512 Hz from 64 Ag/AgCl electrodes inserted into a mesh cap. Horizontal electrooculogram recordings were obtained from flat electrodes placed at the outer canthi of the eyes. A single flat electrode was placed below the participant's right eye to record vertical electrooculogram. Electrode measurements were amplified using an ActiveTwo amplifier (Biosemi, Amsterdam, The Netherlands).

Preprocessing of continuous EEG was done using EEGLAB (Delorme & Makeig, 2004), and artifact rejection, epoching, and extraction were performed using ERPLAB (Lopez-Calderon & Luck, 2014). Continuous EEG was referenced to left and right mastoids, down-sampled to 256 Hz, and band-pass-filtered to 0.1 through 40 Hz. Note that this commonly employed high-pass frequency has been previously determined to be acceptable for relatively slow ERP components, such as the LPP (e.g., Hajcak, Weinberg, MacNamara, & Foti, 2011). Epochs were extracted from 150 ms before to 2,000 ms after the standard and target

Table 3. Frequency of Each Image Type in the Subjective-Smoothness Bins in Experiment 3

Smoothness bin	Negative images	Neutral images	Positive images
Low	41	28	6
Medium	21	30	24
High	13	17	45

displays. Trials with eyeblinks and major eye movements were rejected using ERPLAB's moving-window peak-to-peak algorithm, which detected extreme voltage deflections in the three oculogram channels (voltage threshold = 60 μ V, window width = 200 ms, window step = 50 ms). Trials with extreme voltage deflections in midline electrodes (Oz, POz, Pz, CPz, Cz, FCz, Fz, AFz, Fpz) were rejected using a separate moving-window peak-to-peak procedure (voltage threshold = 70 μ V, window width = 200 ms, window step = 50 ms).

In order to obtain ERPs reflecting differences in subjective smoothness, we calculated the mean smoothness ratings for each trial across participants. A linear regression predicting mean smoothness from the ordinalized frame rate of the standard stimulus was then performed to obtain standardized residuals, which reflected the variability in participants' smoothness ratings that could not be predicted from objective smoothness. These standardized residuals, which served as a behavioral measure of the AMB effect, were then used to group the trials into three categories of subjective smoothness (low, medium, and high). Because the AMB effect is responsive to differences in picture content, there was considerable correspondence between the three bins and the affect categories; the low-smoothness bin consisted predominantly of negative images, and the high-smoothness bin consisted predominantly of positive images, whereas the medium-smoothness bin contained more neutral images than the other bins plus a mix of both positive and negative images (Table 3). (An analysis of trials binned by emotion category rather than smoothness is reported in the Supplemental Material.) ERPs elicited by the target displays were baseline corrected using the 150 ms preceding stimulus onset and were averaged across trials within each subjective-smoothness bin. Artifact rejection resulted in a mean rejection rate of 22.4% of the binned epochs.

Results

For all analyses, reported values are Greenhouse-Geisser corrected when sphericity cannot be assumed, and pairwise comparisons are Bonferroni corrected.

Behavioral results

Stimulus ratings. Arousal and approach/avoidance ratings of the stimuli (Table 1) were submitted to one-way repeated measures ANOVAs, which resulted in the same pattern of results as in Experiment 1 (for details, see the Supplemental Material available online). Time since eating (Table 1) was not significantly correlated with arousal or approach/avoid ratings for positive stimuli ($p = .193$ and $p > .250$, respectively).

Perceived fade smoothness. A 3 (stimulus frame rate) \times 3 (stimulus category) repeated measures ANOVA was performed on the data for perceived fade smoothness of the target (Fig. 4a). There was a main effect of stimulus frame rate, $F(1.04, 18.66) = 17.65$, $p < .001$, $\eta_p^2 = .50$, observed power = .981. Pairwise comparisons revealed significant differences in perceived fade smoothness between the 16-fps condition and both the 24-fps condition and the 48-fps condition ($p = .002$ and $p = .001$, respectively) and a significant difference between the 24-fps condition and the 48-fps condition ($p = .012$); lower frame rate of the standard resulted in higher perceived smoothness of the target's fading. A main effect of stimulus category was also obtained, $F(2, 36) = 6.31$, $p = .004$, $\eta_p^2 = .26$, observed power = .871; negative stimuli were rated as least smooth, and positive stimuli were rated as smoothest (Table 2). Pairwise comparisons revealed a significant difference between positive and negative stimuli ($p = .028$), a nearly significant difference between positive and neutral stimuli ($p = .056$), and no significant difference between neutral and negative stimuli ($p > .250$); there was an overall trend for positive stimuli to be rated as smoother and negative stimuli as less smooth than neutral stimuli. There was no significant interaction between the two factors, $F(2.56, 46.07) = 0.208$, $p = .862$, $\eta_p^2 = .01$. Thus, results showed that negative images were rated as choppiest and positive images as smoothest, again suggesting that subjective temporal acuity was reduced for positive stimuli and increased for negative stimuli.

Stimulus ratings predicting perceived fade smoothness. The same multilevel model used in Experiments 1 and 2 was employed to investigate the effect of image ratings on perceived fade smoothness, controlling for the amount of time since the participant last ate and objective stimulus properties. Results showed that the degree of edges in the stimulus significantly influenced perceived fade smoothness, $\beta = -0.06$, $t(66.47) = -2.01$, $p = .049$; more edges resulted in a less smooth perception of the fade. When the model controlled for the effect of all other variables, approach/avoidance ratings related to perceived fade smoothness at the trend level, $\beta = 0.15$, $t(18.07) = 1.99$, $p = .06$; higher approach ratings resulted in perception of a smoother fade (Fig. 4b). However, this

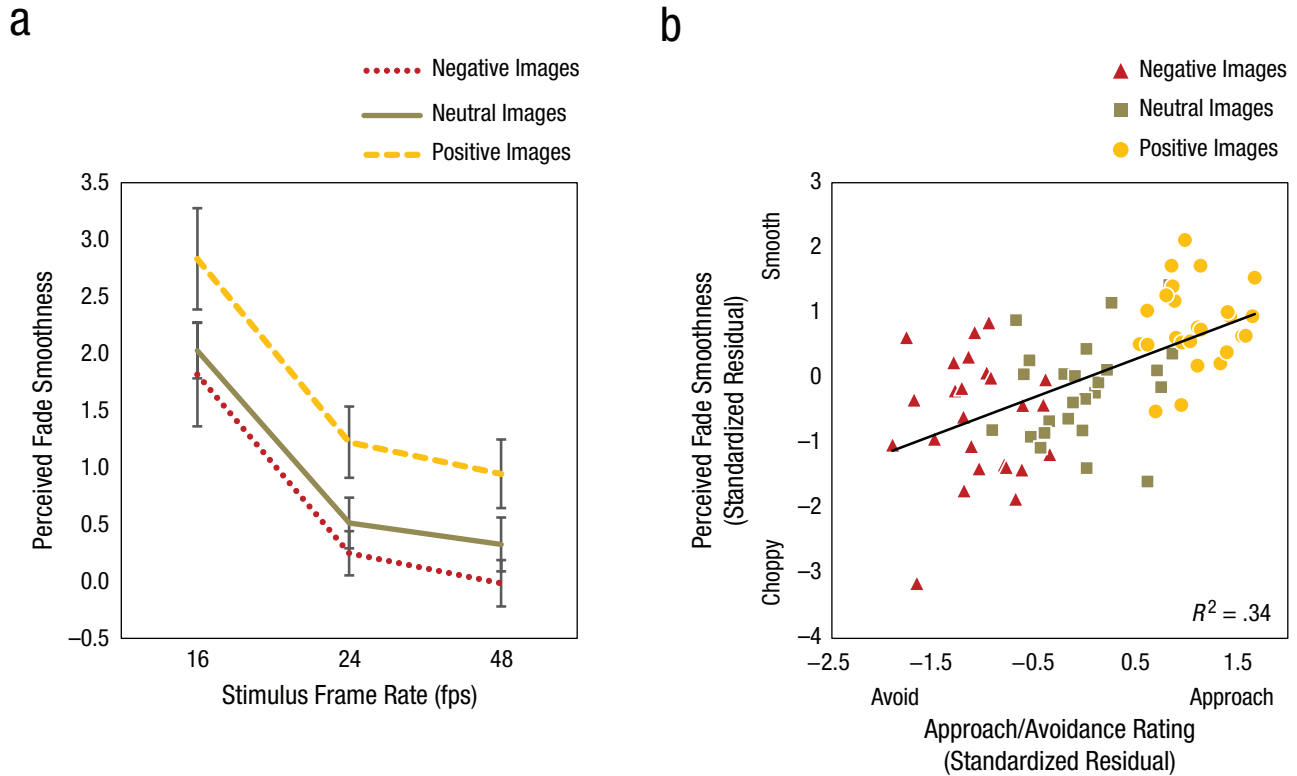


Fig. 4. Affective influences on perceived fade smoothness of the target in Experiment 3. The line graph (a) shows perceived fade smoothness as a function of stimulus frame rate (fps = frames per second), separately for the three stimulus categories. Error bars indicate ± 1 SEM. Note that the trend in these results is the reverse of the trend in the previous experiments because the standard's frame rate, rather than the target's, was varied. The scatterplot (b) shows the relation between the standardized residuals of mean approach/avoidance ratings and perceived fade smoothness after controlling for low-level objective stimulus properties. Each plotted point represents results for a single stimulus, across participants; the category of the stimulus is indicated by the symbol (triangle, square, or circle). Also shown is the best-fitting regression line.

effect was not significant when arousal, time since eating, and objective stimulus characteristics were not included in the model, $\beta = 0.12$, $t(20.61) = 1.77$, $p = .091$. Perceived fade smoothness was not related to amount of contrast, saturation, arousal ratings, or time since eating ($ps > .250$). Thus, as in the previous studies, the overall pattern of results of the multiple-level analysis was that higher levels of elicited approach motivation predicted greater perceived smoothness, an association consistent with speeded time perception and reduced rates of sampling. However, in this experiment, the effect did not reach the conventional level of significance.

Event-related potentials

Early ERPs at the three subjective-smoothness levels. Our primary question concerned whether the behavioral findings of AMB reflected perceptual (rather than merely conceptual) processes, and our goal was to determine when and where on the scalp cortical modulation by AMB could be first observed. Given the connectivity between visual cortex and motivation circuits (Amaral, Behnia,

& Kelly, 2003), we expected the behavioral effects to be associated with ERPs linked to higher-order perceptual processes. To systematically examine modulation of ERP activity by AMB in a principled and conservative data-driven manner, we employed the Mass Univariate ERP Toolbox (Groppe, Urbach, & Kutas, 2011). Using this toolbox, one can test for reliable differences between conditions by creating a difference wave and then performing a series of one-sample t tests across the desired time window while correcting for multiple comparisons.

We created three difference waves to compare the high- and medium-, high- and low-, and medium- and low-subjective-smoothness bins. In each case, the wave for the lower-smoothness bin was subtracted from the wave for the higher-smoothness bin. A separate mass univariate analysis was performed for each of these difference waves, using repeated measures, two-tailed t tests at all 64 scalp electrodes at every time point between 100 and 400 ms (77 time points). This procedure resulted in a total of 4,928 comparisons. Benjamini, Krieger, and Yekutieli's (2006) procedure for controlling

false discovery rate (FDR) was used, with family-wise alpha set to .0167 to correct for multiple comparisons. This particular analysis was recommended by Groppe et al. (2011) for both focal and distributed effects, when it is important to avoid making Type II errors, and when it is likely that a relatively large number of individual inferential tests will fail to reject the null hypothesis.

Significant differences emerged in the high-low and high-medium comparisons, but not the medium-low comparisons. For the comparison of high- and low-smoothness trials, the critical t score was ± 3.82 (which corresponded to a test-wise alpha of .001). Using this criterion, we found 354 significant differences, with an estimated upper bound of 5.9 false discoveries. Two clusters of differences were observed (Fig. 5a): a cluster of negative differences at occipital electrodes, starting at 129 ms and ending at 258 ms, and a cluster of positive differences at frontal and central electrodes, starting at 218 ms and ending at about 352 ms. Most of the differences were in the left hemisphere. The comparison of high- and medium-smoothness trials revealed qualitatively similar results, with the differences reduced in magnitude. For this comparison, the critical t score was ± 4.03 (which corresponded to a test-wise alpha of $< .001$). Using this criterion, we found 224 significant differences, with an estimated upper bound of 3.7 false discoveries. Similar clusters were apparent (Fig. 5b): a cluster of negative differences at occipital electrodes, starting at 137 ms and ending at 152 ms, and a cluster of positive differences at frontal and central electrodes, starting at 277 ms and ending at about 363 ms. Again, most of the differences were present in the left hemisphere.

To illustrate the early negative difference, we created a plot of the waveforms at Iz, a representative electrode (Fig. 5c). This plot reveals a less positive peak in the high-subjective-smoothness bin compared with the medium- and low-subjective-smoothness bins at 200 ms. This difference corresponds to an amplitude modulation by subjective smoothness at the time period of the postsensory P2, an early- to mid-latency positive ERP peak measured at occipitoparietal electrodes (Hackley, Woldorff, & Hillyard, 1990; Qian, Al-Aidroos, West, Abrams, & Pratt, 2012); reporting high smoothness was associated with a reduced amplitude. The visual P2 component has been associated with object discrimination (Rousselet, Husk, Bennett, & Sekuler, 2008) and affective salience (Carretié, Hinojosa, Martín-Loeches, Mercado, & Tapia, 2004; Todd et al., 2012). Thus, this component has been found to be sensitive to subjective modulation of visual perception associated with extraction of information about the meaning of a visual stimulus (Todd et al., 2012). Our findings of smaller amplitude for higher levels of AMB at the time period of the P2 suggest that AMB reflects altered perceptual processing

of approach-motivating stimuli that occurs following stimulus identification.

To illustrate the positive difference later in the ERP, we created plots of the waveforms at F3 and FC5, two representative fronto-central electrodes (Fig. 5d). These plots show a less negative deflection at 300 ms in high-smoothness trials compared with medium- and low-smoothness trials. This difference arises at the beginning of the LPP in frontal and central electrodes. Thus, this result is consistent with a modulation of the LPP onset or the amplitude near its onset, such that higher smoothness is associated with greater initial LPP amplitude at medial and left-lateralized frontal and central electrode sites.

The LPP component at the three subjective-smoothness levels. Because the LPP is canonically sensitive to emotional and motivational salience, we examined its modulation by AMB. We conducted a mass univariate analysis in order to remain consistent with our analytic approach to the early ERP differences and to obtain more precise information regarding the timing and scalp distribution associated with our behavioral effect. The same difference waves and analysis parameters were used for this analysis as for the early-ERP analyses, with the exception that, in this case, we compared the ERPs at every time point between 400 and 1,600 ms (309 time points), for a total of 19,776 comparisons.

Significant differences emerged in the comparison of the high- and low-smoothness bins, but not the comparison of the high- and medium-smoothness bins or the comparison of the medium- and low-smoothness bins. For the comparison of high- and low-subjective-smoothness trials, the critical t score was ± 3.51 (which corresponded to a test-wise alpha of .003). Using this criterion, we found 2,664 significant differences, with an estimated upper bound of 44.5 false discoveries. Two clusters of differences were observed (Fig. 6a): First, positive differences, showing higher amplitudes for images perceived as smoother, were present at frontal and central electrodes at 400 ms, ending at about 914 ms poststimulus, and were observed predominantly in the left hemisphere. Second, a cluster of negative differences, indicating lower amplitudes for images perceived as smoother, was observed at occipital sites beginning at about 594 ms. These differences spread to parietal and central electrode sites and continued until the end of the analyzed period.

Waveforms from frontotemporal electrodes illustrate the slight lateralization evident in the cluster of positive differences (Fig. 6b). The plots indicate that the more pronounced differences in the left hemisphere as compared with the right hemisphere were due to increased

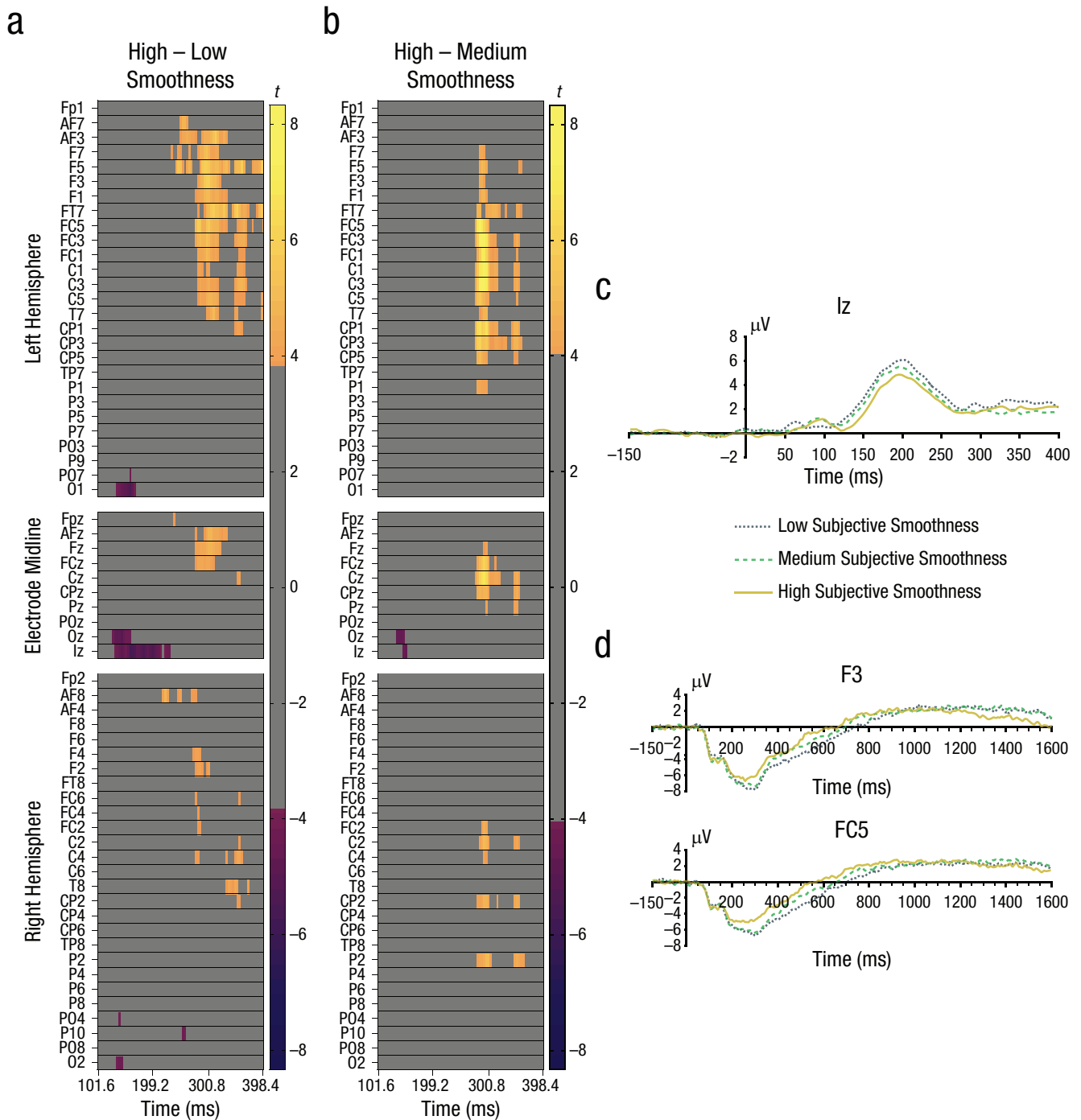


Fig. 5. Results of the mass univariate analyses testing for early differences (100–400 ms) among the event-related potentials (ERPs) from trials in the three subjective-smoothness bins. The plots at the left show the results of t tests testing the difference between ERPs from the (a) high- and low-subjective-smoothness bins and (b) high- and medium-subjective-smoothness bins at all time points and scalp electrodes. For both analyses, the wave for the lower-smoothness bin was subtracted from the wave for the higher-smoothness bin. In (a), the critical t values are ± 3.82 ; in (b), the critical t values are ± 4.03 . The waveforms in (c), from electrode Iz, illustrate the early cluster of differences at occipital electrodes, showing a reduced positive peak in the high-subjective-smoothness bin compared with the medium- and low-subjective-smoothness bins at around 200 ms. The waveforms in (d), from electrodes F3 and FC5, illustrate the later cluster of differences at frontal and central electrodes, showing a reduced negative peak in the high-subjective-smoothness bin compared with the medium- and low-subjective-smoothness bins at around 300 ms.

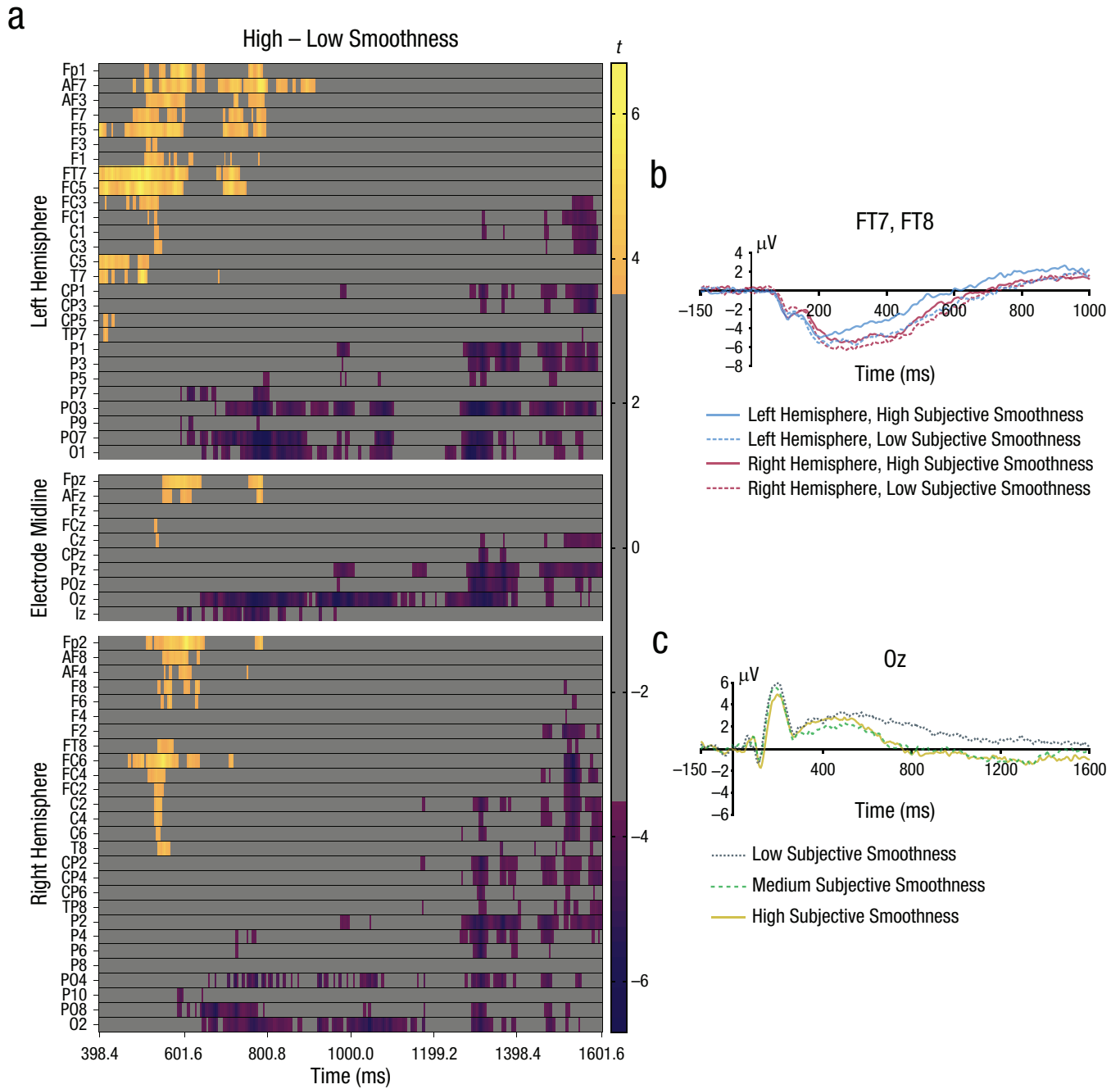


Fig. 6. Results of the mass univariate analysis testing for differences in the late positive potential (LPP) among the three subjective-smoothness bins. The plots in (a) show the results of t tests testing the difference between event-related potentials from the high- and low-subjective-smoothness bins (high smoothness – low smoothness) at all time points and scalp electrodes; the critical t values are ± 3.51 . The waveforms in (b), from electrodes FT7 and FT8, illustrate the earlier cluster of differences, showing increased amplitude in the high-smoothness bin compared with the low-smoothness bin in each hemisphere, and a more pronounced amplitude difference in the left hemisphere. The waveforms in (c), from electrode Oz, illustrate the later cluster of differences, showing higher amplitude in the low-smoothness bin compared with the medium- and high-smoothness bins throughout the examined period.

LPP amplitude in the high-smoothness bin at left-hemisphere sites rather than reduced LPP amplitude in the low-smoothness bin at left-hemisphere sites. Thus, this result is consistent with a slightly lateralized modulation

of the LPP, such that higher smoothness is associated with a larger left-lateralized LPP amplitude.

Plots for the midline posterior electrode (Oz) illustrate the negative differences found in the analysis

(Fig. 6c). These differences were due to lower LPP amplitude at posterior sites in high-smoothness trials compared with low-smoothness trials. Thus, these results indicate that subjective smoothness modulated late ERP activity at occipital and parietal electrode sites.

In summary, subjective smoothness ratings were associated with modulation of a left-lateralized LPP, which is consistent with previous research on appetitive stimuli and the LPP (Gable & Harmon-Jones, 2010). Further, subjective smoothness ratings were associated with differential LPP activity over occipital regions during stimulus presentation, which suggests that extended subjective enhancement of visual-cortex activity, thought to reflect reentrant processes, is associated with the effects of approach motivation on the experience of seeing.

To confirm that the emotion categories in our task elicited canonical LPP patterns, we performed a parallel analysis comparing ERPs for positive and neutral stimuli, negative and neutral stimuli, and positive and negative stimuli (see the Supplemental Material). Overall, positive images were associated with modulation of a left-lateralized LPP, a result consistent with previous research on appetitive stimuli (Gable & Harmon-Jones, 2010), and evoked greatest activation in an early time window (400–650 ms); negative images evoked a large and sustained response both early and late in the LPP time window.

Conclusion. Together, our ERP findings shed light on the behavioral phenomenon of AMB, indicating that AMB is associated with modulation of relatively rapid high-level visual processing driven by meaning extraction as well as later sustained elaboration.

Cross-Experiment Behavioral Analysis

Method

Because our sample size was determined on the basis of power to find main effects of the size observed in our previous studies, we next combined the data from all three experiments to examine potential interactions and conduct further inferential analysis. Some recategorization of the data was necessary: In Experiment 3, we varied the frame rate of the standard stimulus rather than the target stimulus, while still asking participants to indicate how much more or less smooth the target was compared with the standard. This resulted in a reversed pattern of smoothness ratings across the frame rates compared with the pattern in the previous two experiments. In order to correct for this task difference in the combined analysis, we changed the independent

variable to correspond to the objective smoothness of the target compared with standard (choppier, same, and smoother), rather than the frame rate of the varied stimulus.

Across all three experiments, a total of 99 participants provided complete smoothness-rating data (68 female, 31 male; mean age = 20.8 years, $SD = 2.72$). Four participants were removed because of testing error. A further 20 participants were excluded from this analysis for rating neutral stimuli presented at 16 fps as more smooth, on average, than neutral stimuli presented at 48 fps. This left 75 participants (52 female, 23 male; mean age = 21.0 years, $SD = 2.94$) with acceptable data for analysis. Of these participants, 1 had missing data for time since last eating and was excluded only from analyses that required this variable.

Results

Stimulus ratings. Arousal and approach/avoidance ratings of the stimuli (Table 1) were submitted to two separate mixed-design ANOVAs to verify differences among the stimulus categories across the three experiments. For arousal ratings, there was a main effect of stimulus category, $F(1.65, 118.94) = 162.99, p < .001, \eta_p^2 = .69$. All three pairwise comparisons revealed a significant difference ($ps < .001$); neutral images were rated as least arousing and negative images as most arousing. For ratings of approach/avoidance, there was also a main effect of stimulus category, $F(1.56, 112.41) = 230.49, p < .001, \eta_p^2 = .76$. All three pairwise comparisons revealed a highly significant difference ($ps < .001$); compared with neutral stimuli, negative stimuli were rated as more avoidance motivating, and positive stimuli were rated as more approach motivating. Together, these results confirmed that our stimuli elicited the expected pattern of differential arousal and approach motivation. Time since eating was not significantly correlated with arousal or approach/avoidance ratings for positive stimuli, $ps > .250$. There was no effect of experiment on either arousal or approach/avoidance ratings ($ps > .250$), and there was no significant interaction between experiment and stimulus category for arousal ratings ($p = .115$) or for approach/avoidance ratings ($p = .070$).

Perceived fade smoothness. A 3 (objective smoothness) \times 3 (stimulus category) \times 3 (experiment) mixed-design ANOVA was performed on the data for perceived fade smoothness of the target (Fig. 7a). There was a main effect of objective smoothness, $F(1.39, 100.35) = 64.33, p < .001, \eta_p^2 = .47$, observed power = 1.00. All pairwise comparisons between objective smoothness levels were significant ($ps < .001$); higher objective smoothness resulted in higher smoothness ratings. There was a main

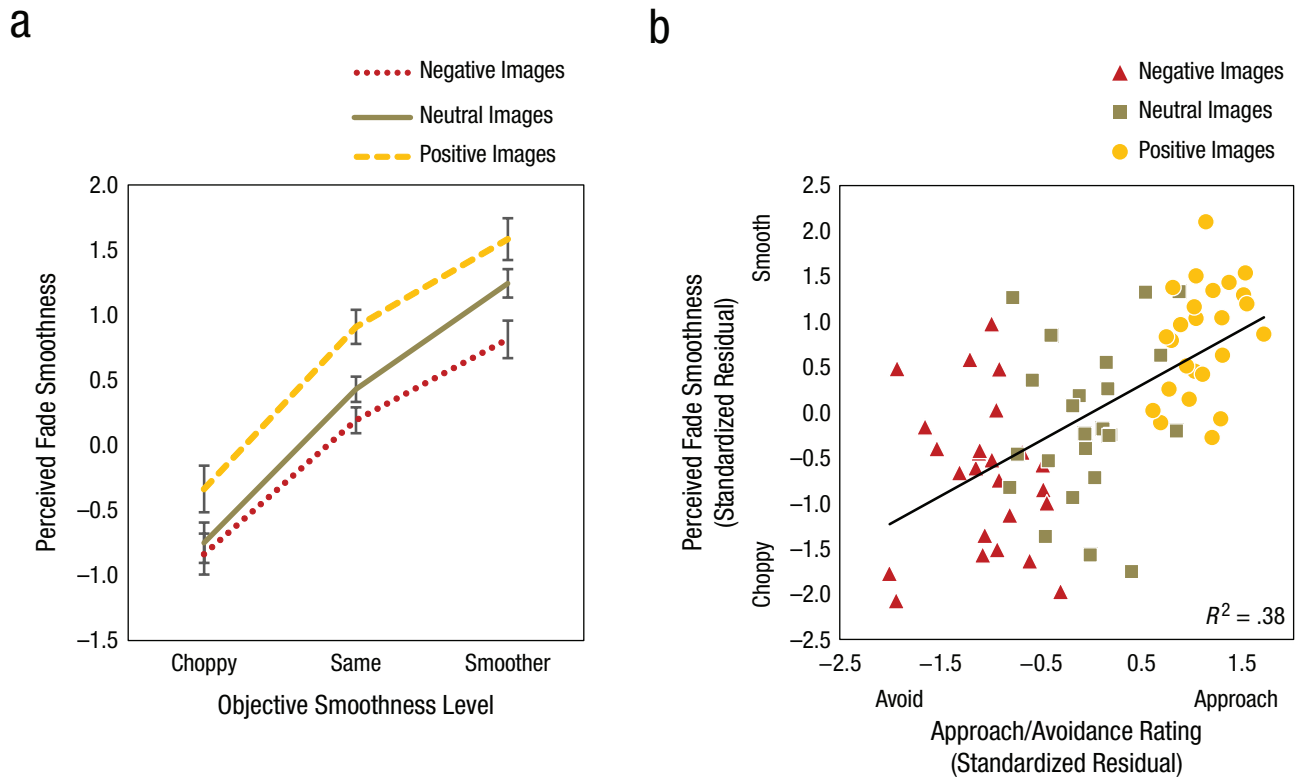


Fig. 7. Affective influences on perceived fade smoothness across all three experiments. The line graph (a) shows perceived fade smoothness of the target as a function of its objective smoothness compared with the standard, separately for the three stimulus categories. Error bars indicate ± 1 SEM. The scatterplot (b) shows the relation between the standardized residuals of mean approach/avoidance ratings and perceived fade smoothness after controlling for low-level objective stimulus properties. Each plotted point represents results for a single stimulus, across participants; the category of the stimulus is indicated by the symbol (triangle, square, or circle). Also shown is the best-fitting regression line.

effect of stimulus category, $F(1.59, 114.54) = 21.77$, $p < .001$, $\eta_p^2 = .23$, observed power = 1.00. Pairwise comparisons revealed a significant difference between negative and neutral stimuli ($p = .013$) and significant differences between positive and both neutral and negative stimuli ($ps < .001$); negative images were rated as least smooth and positive images as most smooth. There was also an interaction between objective smoothness and stimulus category, $F(4, 288) = 3.81$, $p = .005$, $\eta_p^2 = .05$, observed power = .891. Pairwise comparisons revealed that when the target had the same objective smoothness as the standard or was choppy than the standard, negative and neutral images did not differ significantly from one another in subjective smoothness ($p = .124$ and $p > .250$, respectively); all other comparisons of combinations of stimulus category and objective smoothness were significant ($ps < .004$). Thus, positive stimuli were reliably rated as more smooth than neutral stimuli across all levels of objective smoothness, and negative stimuli were rated as less smooth than neutral stimuli only when the stimuli were at the highest level of objective smoothness. In sum, across the experiments, positive images were rated as

more smooth and negative images as less smooth than neutral images, but the difference between negative and neutral images was reliable only at the highest level of objective smoothness.

Overall, positive stimuli modulated subjective smoothness more reliably than negative stimuli did; positive stimuli were rated as significantly more smooth than neutral stimuli in two of the three experiments (the nonsignificant result was just beyond an alpha of .05), whereas negative images were rated as significantly less smooth than neutral images in only one of the three experiments (see Table 4 for results of all pairwise comparisons in the three experiments individually and combined).

There was also a main effect of experiment, $F(2, 72) = 22.31$, $p < .001$, $\eta_p^2 = .38$. Pairwise comparisons revealed that smoothness ratings did not differ overall between Experiments 1 and 2 ($p > .250$), whereas smoothness ratings were significantly higher in Experiment 3 than in Experiments 1 and 2 ($ps < .001$). There was no interaction between experiment and stimulus category ($p > .250$), but there was a significant interaction between

Table 4. Results From the Cross-Experiment Analysis: p Values From the Pairwise Comparisons of Smoothness Ratings

Experiment	Comparison		
	Positive vs. negative images	Positive vs. neutral images	Neutral vs. negative images
1	.012	.007	.242
2	.005	.038	.039
3	.028	.056	.794
Combined	< .001	< .001	.013

experiment and objective smoothness, $F(4, 144) = 7.56$, $p < .001$, $\eta_p^2 = .17$. Simple-effects analyses revealed that for stimuli at the lowest level of objective smoothness, smoothness ratings were significantly higher in Experiment 3 than in Experiment 2 ($p = .002$) and Experiment 1 ($p < .001$), and did not differ significantly between Experiments 1 and 2 ($p = .062$). Similarly, for stimuli at the highest level of objective smoothness, smoothness ratings were higher in Experiment 3 than in Experiment 1 ($p = .007$) and Experiment 2 ($p < .001$), and did not differ significantly between Experiments 1 and 2 ($p > .250$). For stimuli at the intermediate level of objective smoothness, smoothness ratings did not differ between experiments ($p > .250$). The three-way interaction of stimulus category, objective smoothness, and experiment was not significant ($p = .096$). These differences between Experiment 3 and the other two experiments likely reflect the fact that the manipulation of frame rate involved targets in Experiments 1 and 2 but involved the standard in Experiment 3. Yet despite shifts in perceptions of overall smoothness, the effect of approach motivation on relative smoothness ratings remained consistent across the experiments.

Stimulus ratings predicting perceived fade smoothness.

The same multilevel model used in Experiments 1, 2, and 3 was employed to investigate the effect of image ratings on perceived fade smoothness, controlling for time since the participant last ate and objective stimulus properties; experiment was modeled as a random effect. Perceived fade smoothness was significantly influenced by stimulus contrast, $\beta = -0.07$, $t(66.6) = -3.22$, $p = .002$, and degree of edges, $\beta = -0.05$, $t(65.6) = -2.20$, $p = .031$; higher contrast and more edges predicted reduced perceived smoothness. With the higher power provided by using the data from all three experiments, we also found that time since participants had last eaten predicted fade smoothness, $\beta = 0.05$, $t(1779.4) = 2.65$, $p = .008$; more time since eating resulted in higher smoothness ratings. As predicted, approach/avoidance ratings were significantly related to perceived fade smoothness, $\beta = 0.08$, $t(52.6) = 2.96$, $p = .005$; higher approach ratings resulted

in perception of smoother fading (Fig. 7b). This effect was also significant when arousal ratings, time since eating, and objective stimulus characteristics were not included in the model, $\beta = 0.07$, $t(59.86) = 2.55$, $p = .013$. Perceived fade smoothness was not related to saturation ($p > .250$) or arousal ratings ($p = .174$). Thus, the image-level analysis revealed that a higher level of elicited approach motivation predicted greater perceived smoothness, which is consistent with the idea that approach motivation is associated with speeded time perception and reduced rates of sampling.

Discussion

In this study, we employed a novel psychophysical experimental design to examine the subjective experience of the temporal resolution of emotionally relevant stimuli. We demonstrated that the often-noted experience that “time flies when you’re having fun” is embodied in a literal blurring of perceptual experience, or AMB, and its perceptual cortical expression. Together, these experiments demonstrated that high-approach positive stimuli, neutral stimuli, and negative stimuli are associated with distinctly different subjective moment-to-moment perceptual experiences. Although participants accurately differentiated between different stimulus frame rates overall, at each individual frame rate, approach motivation resulted in a smoother percept, that is, AMB. In Experiment 2, we replicated the findings after altering the wording of the task to control for potential associations between positive and negative affect and the words *smooth* and *choppy*, respectively. In Experiment 3, we found AMB modulation of ERP components associated with altered perceptual processing and reentrant processing of the stimulus as the fade unfolded. Experiments 2 and 3 provide convergent evidence suggesting that our behavioral results were due to altered experience of seeing rather than demand characteristics. Such AMB is consistent with models positing a mechanism of altered temporal sampling for affectively salient events.

Altered experience of duration is often explained in terms of increased or decreased speed of an internal

pacemaker (e.g., Burle & Casini, 2001; Droit-Volet et al., 2004; Wearden, Philpott, & Win, 1999). Our experiment was designed to probe whether putative changes in pacemaker speed influence moment-to-moment temporal experience, such that enhanced subjective temporal acuity, consistent with the experience of time being slowed, leads to visual stimuli being perceived as more choppy, whereas reduced subjective temporal acuity, consistent with the experience of time speeding up, leads to visual stimuli being perceived as more smooth. Previous studies have shown that negative stimuli tend to be judged as longer in duration than neutral stimuli (Dirnberger et al., 2012; Droit-Volet et al., 2004), which should have resulted in a longer subjective duration for each frame of the fading stimulus and thus greater ease in distinguishing frames in our experiments. Similarly, there is evidence that high-approach positive stimuli are judged as shorter in duration than neutral items (Gable & Poole, 2012). In our experiments, this would have resulted in a shorter perceived duration for each frame in the stimulus fade, and thus less ease of distinguishing frames and a “smoother” temporal percept. Our results are consistent with these predictions and support a view of opposing patterns of temporal sampling for high-approach and high-avoidance stimuli—specifically, decreased temporal sampling for high-approach stimuli relative to high-avoidance stimuli. In turn, our findings have implications for interpretation of several models.

The striatal beat-frequency model (Matell & Meck, 2004) is a recent model that links behavioral findings of temporal duration to neurobiological substrates mediating interval timing. In this model, oscillating cortical and thalamic neuron ensembles code for subjective temporal duration; speeded neural oscillations are analogous to an increased clock speed of the pacemaker. This model proposes that dopamine modulates clock speed, and specifically that an increase in dopamine results in a slowed subjective sense of time (Meck, Penney, & Pouthas, 2008). Dopamine’s role in prediction and expectation of rewards is well established (Berridge & Robinson, 1998), and thus we expect that dopamine plays a role in AMB; however, our results suggest that the relationship is likely more complex than a straightforward association between increased sampling and higher levels of dopamine. Future research can employ targeted genotyping and pharmacological manipulations to examine dopaminergic influences on patterns of neural activation associated with AMB.

Previous research has shown the crucial importance of attention in evaluations of temporal duration (Buhusi & Meck, 2009). Some evidence suggests that subjective temporal distortions are at least partly due to encoding efficiency. Mundane stimuli are judged as shorter,

whereas novel stimuli are judged as longer (Eagleman & Pariyadath, 2009). This line of research does not offer an adequate explanation for our data, because both the negative and the positive stimuli used in our study likely engaged more attentional resources than the neutral images, and yet they had opposing effects on perceived stimulus smoothness. Our results are more consistent with evidence that greater attentional deployment to tracking the passage of time results in longer perceived duration (Brown, 1997; Burle & Casini, 2001). Negative, avoidance-motivating stimuli may result in increased deployment of attention to the passage of time (when one wants to get out of a situation rapidly, the passage of time becomes more salient). In contrast, positive, approach-motivating stimuli may serve as a distraction from timekeeping, as attention may become focused on reward acquisition (Gable & Harmon-Jones, 2008). Thus, deployment of attention to fine-grained temporal perceptual information may be reduced.

Our electrophysiological analyses revealed that AMB modulated early (at ~200 ms) ERP amplitude at occipital electrode sites and also modulated a slightly left-lateralized fronto-central LPP as well as a later occipital LPP. The time period and scalp distribution of the early occipital modulation is consistent with the visual P2, which has been associated with object discrimination (Rousselle et al., 2008). In our experiment, high subjective smoothness was associated with a reduced positive deflection at this time period and spatial distribution, which may indicate modulation of high-level perceptual processes by AMB. Previous research has revealed modulation of a posterior P2 by emotional salience and perceptual vividness (Todd et al., 2012). Such findings are consistent with modulation of visual processing by subjective salience at a latency sufficient to allow extraction of meaning. This pattern of response in the current study is also consistent with previously observed attenuation of the amplitude of the posterior P2 due to attentional processing of visual stimuli (Hackley et al., 1990).

The association between subjective smoothness and the LPP links our findings to previous studies of the effects of affective salience on ERP components. The LPP is modulated by the affective content of picture stimuli (Cuthbert et al., 2000), and we report here that subjective smoothness is highly associated with the affective content of picture stimuli. Moreover, our LPP results indicate that AMB reflects not only an early “flash” of altered perceptual processing, but also more sustained visual processing likely driven by reentrant processes. The modulation of frontal negativity observed at 300 ms poststimulus may reflect frontal cortical contributions to such reentrant processes, though future studies will be required to localize such effects precisely.

At left-lateralized frontal and central sites, we also observed increased positive activation for high-smoothness images relative to low-smoothness images in both the early-ERP analysis and the LPP analysis, predominantly at 300 to 800 ms poststimulus. The left lateralization is consistent with previous findings showing that positively valenced content is associated with a left-lateralized LPP (Cunningham, Espinet, DeYoung, & Zelazo, 2005; van de Laar, Licht, Franken, & Hendriks, 2004). This component has previously been associated with a local spatial attentional bias that can be caused by approach-motivating images (Gable & Harmon-Jones, 2010). Recent research has established robust attentional prioritization of stimuli associated with reward (Chelazzi, Perlato, Santandrea, & Della Libera, 2013). Thus, one interpretation of our LPP findings is that greater smoothness is perceived when local attentional processing is induced by approach-motivating stimuli. Future investigations involving independent manipulations of attentional focus may test this possibility.

At later latencies at occipital sites, we observed the reverse pattern of higher LPP amplitudes in response to low subjective smoothness. Both emotional arousal and sustained attentional engagement modulate LPP amplitude (Gable & Adams, 2013). As the present study did not manipulate sustained attention, it is not possible to tease apart the possible effects of the two. Future studies can disentangle attentional and affective influences on the late LPP in this task. Nevertheless, it is important to note that this will be a daunting endeavor, as the LPP is a late ERP deflection reflecting activity of large-scale networks in a highly context-dependent fashion. Thus, it is difficult to interpret how the direction of differences in amplitude reflects the degree of activation in underlying brain regions. We prefer a more conservative interpretation of LPP differences as simply reflecting neural discrimination between conditions. In this light, the importance of our LPP findings is that they show how the behavioral effect of AMB is reflected in ongoing neural processing in real time during perception of the stimulus. Note that though there was a very evident LPP in the ERPs, a slight attenuation of the LPP may have occurred because of our 0.1-Hz high-pass filter (Hajcak et al., 2011).

In summary, we have reported novel evidence that stimulus value influences subjective perceptual experience across time. Specifically, appetitive stimuli elicit perception of a “blurred” frame rate characteristic of speeded motion, and negative stimuli elicit the opposite effect. Our ERP findings shed light on the behavioral phenomenon of AMB we have identified, suggesting that approach-motivated perception of speeded time is associated with modulation of high-level visual processing as well as later sustained elaboration. Together, our

results demonstrate that the motivational salience of appetitive stimuli is embodied directly in the subjective experience of moment-to-moment visual perception. Such findings have implications for models of the mechanisms underlying time perception in humans. Future research can further examine the influence of stimulus value on objective acuity, to determine whether AMB results in less accurate discrimination of stimulus details, as well as the neurobiological substrates of the AMB phenomenon.

Action Editor

Eddie Harmon-Jones served as action editor for this article.

Author Contributions

K. H. Roberts and R. M. Todd developed the study concept and design. K. H. Roberts performed the data analysis and interpretation under the supervision of G. Truong and R. M. Todd. K. H. Roberts drafted the manuscript, and G. Truong, A. Kingstone, and R. M. Todd provided critical revisions. All the authors approved the final version of the manuscript for submission.

Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

Funding

This research was supported by a Natural Sciences and Engineering Research Council (NSERC) Discovery grant (RGPIN-2014-04202) to R. M. Todd and by a grant from the Leaders Opportunity Fund of the Canadian Foundation for Innovation (32102) to R. M. Todd.

Supplemental Material

Additional supporting information can be found at <http://journals.sagepub.com/doi/suppl/10.1177/0956797617702698>

References

- Amaral, D., Behniea, H., & Kelly, J. (2003). Topographic organization of projections from the amygdala to the visual cortex in the macaque monkey. *Neuroscience*, *118*, 1099–1120. doi:10.1016/S0306-4522(02)01001-1
- Angrilli, A., Cherubini, P., Pavese, A., & Mantredini, S. (1997). The influence of affective factors on time perception. *Perception & Psychophysics*, *59*, 972–982.
- Bates, D., Maechler, M., Bolker, B., & Walker, S. (2014). lme4: Linear mixed-effects models using ‘Eigen’ and S4 [Computer software]. Retrieved from <http://cran.r-project.org/package=lme4>
- Benjamini, Y., Krieger, A. M., & Yekutieli, D. (2006). Adaptive linear step-up procedures that control the false discovery rate. *Biometrika*, *93*, 491–507. doi:10.1093/biomet/93.3.491

- Berridge, K. C., & Robinson, T. E. (1998). What is the role of dopamine in reward: Hedonic impact, reward learning, or incentive salience? *Brain Research Reviews*, *28*, 309–369. doi:10.1016/S0165-0173(98)00019-8
- Brown, S. W. (1997). Attentional resources in timing: Interference effects in concurrent temporal and nontemporal working memory tasks. *Perception & Psychophysics*, *59*, 1118–1140. doi:10.3758/BF03205526
- Buhusi, C. V., & Meck, W. H. (2009). Relative time sharing: New findings and an extension of the resource allocation model of temporal processing. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*, 1875–1885. doi:10.1098/rstb.2009.0022
- Burle, B., & Casini, L. (2001). Dissociation between activation and attention effects in time estimation: Implications for internal clock models. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 195–205. doi:10.1037/0096-1523.27.1.195
- Carretié, L., Hinojosa, J. A., Martín-Loeches, M., Mercado, F., & Tapia, M. (2004). Automatic attention to emotional stimuli: Neural correlates. *Human Brain Mapping*, *22*, 290–299. doi:10.1002/hbm.20037
- Chelazzi, L., Perlato, A., Santandrea, E., & Della Libera, C. (2013). Rewards teach visual selective attention. *Vision Research*, *85*, 58–72. doi:10.1016/j.visres.2012.12.005
- Cunningham, W. A., Espinet, S. D., DeYoung, C. G., & Zelazo, P. D. (2005). Attitudes to the right- and left: Frontal ERP asymmetries associated with stimulus valence and processing goals. *NeuroImage*, *28*, 827–834. doi:10.1016/j.neuroimage.2005.04.044
- Cuthbert, B. N., Schupp, H. T., Bradley, M. M., Birbaumer, N., & Lang, P. J. (2000). Brain potentials in affective picture processing: Covariation with autonomic arousal and affective report. *Biological Psychology*, *52*, 95–111.
- Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*, 9–21. doi:10.1016/j.jneumeth.2003.10.009
- Dimberger, G., Hesselmann, G., Roiser, J. P., Preminger, S., Jahanshahi, M., & Paz, R. (2012). Give it time: Neural evidence for distorted time perception and enhanced memory encoding in emotional situations. *NeuroImage*, *63*, 591–599. doi:10.1016/j.neuroimage.2012.06.041
- Droit-Volet, S., Brunot, S., & Niedenthal, P. (2004). Perception of the duration of emotional events. *Cognition & Emotion*, *18*, 849–858. doi:10.1080/02699930341000194
- Eagleman, D. M., & Pariyadath, V. (2009). Is subjective duration a signature of coding efficiency? *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*, 1841–1851. doi:10.1098/rstb.2009.0026
- Gable, P. A., & Adams, D. L. (2013). Non-affective motivation modulates the sustained LPP (1,000–2,000 ms). *Psychophysiology*, *50*, 1251–1254. doi:10.1111/psyp.12135
- Gable, P. A., & Harmon-Jones, E. (2008). Approach-motivated positive affect reduces breadth of attention. *Psychological Science*, *19*, 476–482. doi:10.1111/j.1467-9280.2008.02112.x
- Gable, P. A., & Harmon-Jones, E. (2010). Late positive potential to appetitive stimuli and local attentional bias. *Emotion*, *10*, 441–446. doi:10.1037/a0018425
- Gable, P. A., & Poole, B. D. (2012). Time flies when you're having approach-motivated fun: Effects of motivational intensity on time perception. *Psychological Science*, *23*, 879–886. doi:10.1177/0956797611435817
- Groppe, D. M., Urbach, T. P., & Kutas, M. (2011). Mass univariate analysis of event-related brain potentials/fields I: A critical tutorial review. *Psychophysiology*, *48*, 1711–1725. doi:10.1111/j.1469-8986.2011.01273.x
- Hackley, S. A., Woldorff, M., & Hillyard, S. A. (1990). Cross-modal selective attention effects on retinal, myogenic, brainstem, and cerebral evoked potentials. *Psychophysiology*, *27*, 195–208. doi:10.1111/j.1469-8986.1990.tb00370.x
- Hajcak, G., Weinberg, A., MacNamara, A., & Foti, D. (2011). ERPs and the study of emotion. In S. J. Luck & E. S. Kappenman (Eds.), *The Oxford handbook of event-related potential components* (pp. 441–472). Retrieved from <http://www.oxfordhandbooks.com/view/10.1093/oxfordhb/9780195374148.001.0001/oxfordhb-9780195374148-e-016>
- Lambrechts, A., Mella, N., Pouthas, V., & Noulhiane, M. (2011). Subjectivity of time perception: A visual emotional orchestration. *Frontiers in Integrative Neuroscience*, *5*, Article 073. doi:10.3389/fnint.2011.00073
- Lang, P. J., Bradley, M. M., & Cuthbert, B. N. (2008). *International Affective Picture System (IAPS): Affective ratings of pictures and instruction manual* (Technical Report A-8). Gainesville, FL: University of Florida.
- Lopez-Calderon, J., & Luck, S. J. (2014). ERPLAB: An open-source toolbox for the analysis of event-related potentials. *Frontiers in Human Neuroscience*, *8*, Article 213. doi:10.3389/fnhum.2014.00213
- Matell, M. S., & Meck, W. H. (2004). Cortico-striatal circuits and interval timing: Coincidence detection of oscillatory processes. *Cognitive Brain Research*, *21*, 139–170. doi:10.1016/j.cogbrainres.2004.06.012
- Meck, W. H. (1996). Neuropharmacology of timing and time perception. *Cognitive Brain Research*, *3*, 227–242. doi:10.1016/0926-6410(96)00009-2
- Meck, W. H., Penney, T. B., & Pouthas, V. (2008). Cortico-striatal representation of time in animals and humans. *Current Opinion in Neurobiology*, *18*, 145–152. doi:10.1016/j.conb.2008.08.002
- Noulhiane, M., Mella, N., Samson, S., Ragot, R., & Pouthas, V. (2007). How emotional auditory stimuli modulate time perception. *Emotion*, *7*, 697–704. doi:10.1037/1528-3542.7.4.697
- Phelps, E. A., Ling, S., & Carrasco, M. (2006). Emotion facilitates perception and potentiates the perceptual benefits of attention. *Psychological Science*, *17*, 292–299. doi:10.1111/j.1467-9280.2006.01701.x
- Qian, C., Al-Aidroos, N., West, G., Abrams, R. A., & Pratt, J. (2012). The visual P2 is attenuated for attended objects near the hands. *Cognitive Neuroscience*, *3*, 98–104. doi:10.1080/17588928.2012.658363
- R Core Team. (2014). R: A language and environment for statistical computing (Version 3.3.1) [Computer software]. Retrieved from <http://www.r-project.org>

- Rousselet, G. A., Husk, J. S., Bennett, P. J., & Sekuler, A. B. (2008). Time course and robustness of ERP object and face differences. *Journal of Vision*, *8*(12), Article 3. doi:10.1167/8.12.3
- Todd, R. M., Ehlers, M. R., Müller, D. J., Robertson, A., Palombo, D. J., Freeman, N., . . . Anderson, A. K. (2015). Neurogenetic variations in norepinephrine availability enhance perceptual vividness. *Journal of Neuroscience*, *35*, 6506–6516. doi:10.1523/JNEUROSCI.4489-14.2015
- Todd, R. M., Talmi, D., Schmitz, T. W., Susskind, J., & Anderson, A. K. (2012). Psychophysical and neural evidence for emotion-enhanced perceptual vividness. *Journal of Neuroscience*, *32*, 11201–11212. doi:10.1523/JNEUROSCI.0155-12.2012
- van de Laar, M. C., Licht, R., Franken, I. H. A., & Hendriks, V. M. (2004). Event-related potentials indicate motivational relevance of cocaine cues in abstinent cocaine addicts. *Psychopharmacology*, *177*, 121–129. doi:10.1007/s00213-004-1928-1
- Wearden, J. H., Philpott, K., & Win, T. (1999). Speeding up and (. . .relatively. . .) slowing down an internal clock in humans. *Behavioural Processes*, *46*, 63–73. doi:10.1016/S0376-6357(99)00004-2