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EEG measures of brain activity reveal that smoking-related images capture the attention of smokers outside of awareness

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ABSTRACT

The capture of attention by substance-related stimuli in dependent users is a major factor in the maintenance and/or cessation of substance use. The present study examined the automaticity of this process in smokers, as well as the effects of craving. Event-related potential (ERP) measures of spatial-attention allocation (N2pc) and extended target processing (SPCN) were isolated during an object-substitution masking (OSM) task that disrupted the perceptual visibility of smoking-related and office-related targets. Each participant completed two experimental sessions: one in which they were deprived of nicotine for a period of several hours prior to the session (craving), and one before which they were allowed to smoke (non-craving). Results were consistent with an account of automatic attentional capture by smoking-related images outside of awareness, with masked trials yielding a selective enhancement of the attention-sensitive N2pc in response to these images, but in the absence of a corresponding behavioral enhancement on those trials. Finally, the manipulation of craving appeared to increase the overall task demand, yielding an enhancement of the SPCN component across target type and masking conditions. Together, these results suggest that smoking-related visual stimuli in the environment can capture the attention of smokers outside of awareness, in what seems to be an automatic process.

1. Introduction

1.1. Substance-related stimuli influence visual attention

The capture of visual attention by substance-related images in dependent users is an example of a broader phenomenon wherein behaviorally relevant stimuli affect attention. The way in which substance-related images bias attention has been examined using both behavioral and neural measures. These studies reported some mixed results, suggesting attentional capture by substance-related images in some cases, and repulsion in others. For example, attention to substance-related cues has been probed using the addiction Stroop task, wherein participants tend to be slower to report the font color of a substance-related word relative to that of a neutral word, presumably due to the capture of attention by the semantic content of the addiction-related word (Cox et al., 2006; Munafo et al., 2003). Similarly, alcohol-related images embedded in an attentional blink task have been shown to capture the attention of alcoholics, with alcohol-related images being less susceptible to the effects of the attentional blink in heavy social drinkers than in light drinkers (Tibboel et al., 2010).

In accordance with effects predicted by the modulation of the allocation of spatial attention (Posner, 1980), subjects detect a visual target more quickly when it is presented in the same location as a previously occurring substance-related image. This experimental setup, known as the dot-probe paradigm, has provided behavioral evidence of attentional biases in smokers (Bradley et al., 2003; Ehrman et al., 2002), cocaine addicts (Franken et al., 2000), and alcoholics (Field et al., 2004; Stormark et al., 1997). Overt measures of attention, such as eye tracking, have provided converging results, with obese patients showing a persistent bias toward food-related stimuli as measured through eye tracking (Castellanos et al., 2009), although other eye-tracking experiments have yielded somewhat mixed results in this regard (Nijs et al., 2010).

In addition to effects of attentional capture, biases driven by substance-related content can also sometimes manifest as an apparent aversion to addiction-related images. For example, an eye-tracking

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experiment showed that cigarette smokers tend to avert their attention from health warnings on cigarette labels (Maynard et al., 2014). Another study probing the N2pc, a hallmark ERP index of attentional allocation toward target stimuli, showed that cigarette smokers may under some circumstances shift attention away from targets containing a smoking-related image (Donohue et al., 2016b). Such a counter-intuitive finding suggests that in the context of smoking-related images, which alone do not present a rewarding experience, smokers may attempt to suppress visual and attentional processing of those stimuli. Specifically, when the smoking-related nature of the stimuli is not germane to the primary task, and when those stimuli do not indicate a greater probability or availability of reward, the subject may attempt to ignore them in a conscious, effortful exercise in cognitive control.

1.2. Craving as a factor

The influence of craving as a motivational state is one factor that distinguishes the attentional effects of substance-related stimuli from other potentially behaviorally relevant stimuli. Extensions of the incentive salience theory of substance dependence claim that craving and the attention-capturing effects of substance-related cues are mutually excitatory, constituting a positive feedback loop (Robinson and Berridge, 1993; Franken, 2003; Ryan, 2002). Specifically, these models predict that craving brought on by substance deprivation has a potentiating effect on the capture of attention by substance-related cues, the exposure to which in turn increases levels of craving in users (Field and Cox, 2008). Other models have extended these predictions to describe a process of automatic attentional capture, wherein conditions of deprivation (i.e., craving) lead to greater capture of attention by substance-related cues (Tiffany and Conklin, 2000). Because the attentional bias toward substance-related stimuli can undermine successful cessation of use, particularly in the case of smokers (Waters et al., 2003), understanding the dynamics and potency of these effects is an important direction for addiction research. Specifically, knowing whether the capture of attention by substance-related stimuli is automatic or is subject to the effortful control of the user, and how this process may be influenced by deprivation, has implications for the development and targetting of cessation strategies. For example, if the capture of attention occurs in the absence of awareness, but only if the viewer is in a state of craving, attenuating the effects of deprivation becomes a reasonable target for intervention, whereas if the attentional capture occurs automatically, regardless of craving, then raising awareness through vigilance may be a more effective strategy.

1.3. Examining the automaticity of attentional effects

In order to probe the automaticity of addiction-related attentional capture, as well as the possible influence of craving on this process, it is useful to examine the extent to which the process occurs in the absence of explicit awareness. To establish any process as occurring in the absence of visual awareness, experimenters implement a logical structure formalized by the dissociation paradigm. In this paradigm, experimenters introduce a manipulation, such as visual masking, that reduces the visibility of relevant stimulus content. Then, explicit behavioral measures of stimulus processing are tracked in conjunction with implicit (often neural) measures of the same process. In the case of the present study, it is assumed that processes of rapid attentional capture reflected in modulations of the N2pc can be dissociated from processes ultimately leading to target-content awareness, in line with accounts of attention and consciousness as distinct phenomena (Lamme, 2003; Koch and Tsuchiya, 2007). Furthermore, the processing of such attentionally relevant information, independent from those processes underlying explicit perceptual awareness, may be considered subliminal, as per the taxonomy of conscious processes outlined by Dehaene et al. (2006). Applied to the phenomenon of attentional capture by substance-related stimuli, the logic of this paradigm dictates that if an implicit measure of attentional biases (such as an enhancement of the N2pc) is less disrupted by the visual presentation manipulation than an explicit behavioral measure of such biases, then some degree of unconscious attentional capture with respect to relevant stimulus content is taking place (Reingold and Merikle, 1988).

1.4. Object-substitution masking (OSM)

As a method for disrupting visual awareness of presented images, object-substitution masking (OSM) is especially well suited for the question at hand. In OSM, a brief (∼ 20–50 ms) array, consisting of distracters and a single target at an unpredictable lateralized location, is presented. Within this presented array, the target is denoted, for example by the presence of four small dots at its corners. For half of the trials, this brief flash of the array and the four-dot target marker appear and offset together as one unified event, which leaves the visibility of the saliently cued target intact. However, for the other half of trials, the target perceptibility is masked by the incorporation of a delayed offset (∼ 300–500 ms) of the four-dot cue relative to the rest of the array, resulting in decreased target visibility (Enns and Di Lollo, 2000). Although the mechanism of this disruption of visual awareness is still an active topic of research, the most favored account describes a process of visual perceptual hypothesis testing by the brain subserved by iterative reentrant signaling in anatomically early visual cortical areas. Specifically, it has been posited that the initial array triggers a provisional hypothesis as to the identity of the target. The reentrant signal carrying the initial array and target information is then compared and convolved with the ongoing feed-forward signal, which carries either nothing in the case of unmasked trials, or the target-surrounding four-dot cue in the case of masked trials. For masked trials, this convolution process is thought to result in the substitution of the representation of the mask-inducing four-dot cue alone for the representation of the target (Di Lollo et al., 2000). This reentrant signaling mechanism of OSM has been supported by a number of studies employing neural measures. For example, high-temporal-resolution measures (i.e., EEG and MEG) have shown that the first measurable difference reflecting effective masking in the delayed cue-offset condition occurs between 130 and 170 ms post-stimulus over mid-occipital cortex, a time window consistent with a reentrant process occurring in primary visual cortex (Boehler et al., 2008; Harris et al., 2013). In addition, hemodynamic measures of brain activity have modeled this index of effective masking by object substitution as arising from primary visual cortex, and its interaction with the deployment of spatial attention to V1 and downstream visual cortical regions (Weidner et al., 2006).

1.5. Probing automatic attentional capture during OSM

Masking by object substitution has been used in conjunction with neural measures to examine the automaticity of a number of cognitive and perceptual processes. Most relevant to the question of how substance-dependence-related images may drive attention are findings pertaining to the N2pc measure of visual spatial attention allocation. The N2pc is an enhanced negative-polarity ERP peaking during the 200–300 ms post-stimulus time window over parieto-occipital scalp sites contralateral to the direction of spatial attention allocation (Woodman and Luck, 1999). In the context of OSM, the N2pc has been shown in some cases to scale with the efficacy of masking, exhibiting a lower mean amplitude when the lateralized target items go unseen in the masked condition relative to those that are detected in that condition (Harris et al., 2013). In other studies, the N2pc appears to be independent of the low-level reentrant signaling mechanism of OSM, showing no such modulation as a function of visual awareness (Prime et al., 2011; Woodman and Luck, 2003). In addition, the MEG analog of the N2pc is enhanced in response to targets containing previously rewarded color features during OSM, regardless of whether those targets were seen by the subject (Harris et al., 2016). Whether the presence of

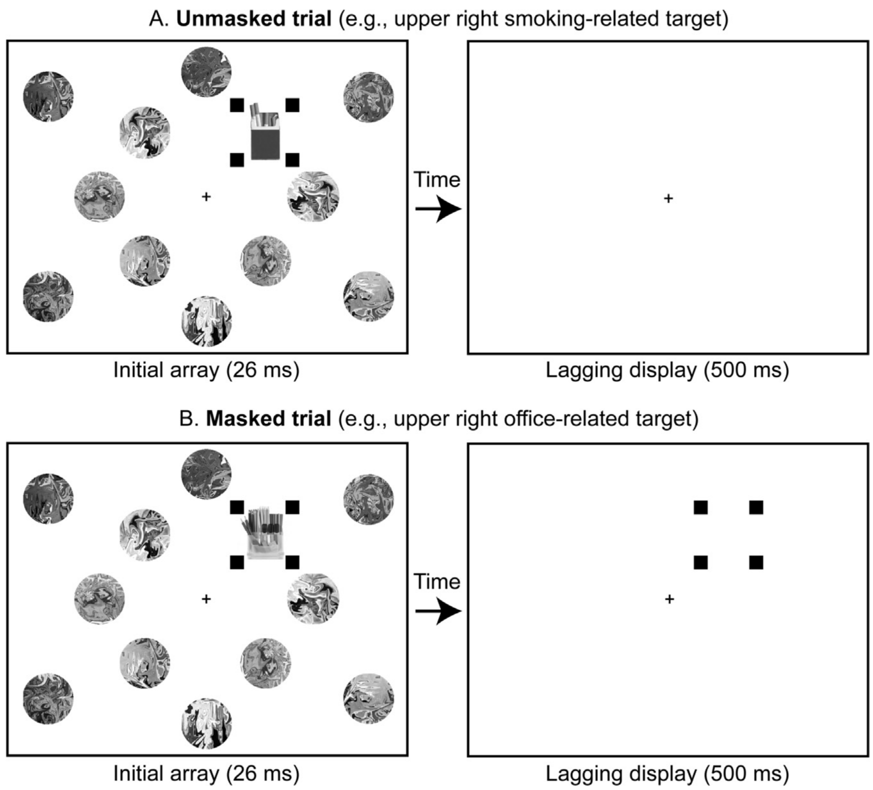

Fig. 1. Object-substitution masking (OSM) task. A. Unmasked trials consisted of a briefly presented (26 ms duration) array composed of 11 cropped circular distracters, a four-square cue denoting the target location, and either a target depicting a smoking-related image, an office-related image, or no image at all (here, a package of cigarettes is depicted). This was followed by 500 ms of only the fixation cross. B. For masked trials, the same briefly presented initial array was followed by a 500 ms duration fixation screen containing only the delayed-offset four-square cue (here, a packet of pencils is depicted). For every trial, subjects completed a three-alternative forced choice task in which they identified the content of the target location of the initial array as either a smoking-related object, an office-related object, or empty space. Both trial types were followed by an inter-trial interval of a randomly selected duration jittered between 700 and 900 ms.

substance-related stimuli exerts the same automatic effect of attentional capture, and how craving affects this and other related visual cognitive processes, is the focus of the present study.

2. Methods

2.1. Participants

Twenty-nine smokers participated in the experiment, with seven ultimately being excluded due to excessive artifacts in their EEG data, yielding a total of 22 participants completing two sessions (craving and non-craving; 5 females, one left-handed; mean age 26.8 years). The order of sessions was counterbalanced across subjects. For the craving session, participants abstained from smoking for 3 h under direct supervision, whereas for the non-craving session, subjects were allowed to smoke a cigarette immediately prior to the measurement. Participants were recruited through local advertisements and initially screened using self-report measures of smoking, with only habitual smokers (i.e., 10 or more cigarettes per day) being accepted. Additional questionnaires measuring levels of smoking and nicotine dependence (Fagerstrom Test for Nicotine Dependence, or FTND)(Heatherton et al., 1991), as well as levels of craving (the Questionnaire for Smoking Urges, or QSU)(Tiffany and Drobes, 1991), were administered prior to participation. The QSU was administered prior to the commencement of each session in order to measure changes in the level of craving associated with deprivation. Informed consent was obtained for all participants in accordance with the protocol approved by the Institutional Review Board of the Otto-von-Guericke University in Magdeburg, Germany. All participants were compensated for their time (6 euros per hour, including supervised deprivation periods, for a total of 60 euros) and task performance.

2.2. Stimuli and task

2.2.1. General

The experimental task was created using the Presentation software package (Neurobehavioral Systems, Albany, CA). Stimuli were presented in the EEG chamber via back projection with a refresh rate of 75 Hz onto a 65 cm by 50 cm screen with a resolution of 1280 by 1024 pixels at a viewing distance of one meter. The target image set comprised two categories, smoking-related objects and office supplies, matched for average luminance and general geometric properties (as used in Donohue et al., 2016b). Specifically, every image in one category had a corresponding 'twin' image in the other category, such as an open pack of cigarettes being matched with a similarly oriented open box of pencils. All images were converted to grayscale and all text was removed from the objects. Distracter images were cropped circular grayscale images of objects, 'liquefied' using Adobe Photoshop (Adobe Systems, Inc., San Jose, CA) as in Harris et al. (2013). Each target category set, as well as the set of distracters, contained 40 possible images. Targets were sized such that the object content, surrounded by a background-matched circular area, was matched in size to the distracters, occupied cropped circular areas with a diameter of 5 cm (equivalent at a one meter viewing distance to 2.9 degrees).

2.2.2. Target-object familiarity task

Before the object-substitution masking task, subjects were familiarized with the two categories of target images (i.e., office images and matched smoking-related images). Specifically, in this familiarization task each possible target, along with a corresponding text label of 'office' or 'smoking', were presented along the vertical meridian, with the text above fixation, and the target below, at an eccentricity equal to that ultimately used for the target locations in the OSM task (see below). Participants viewed one object at a time, with the object remaining on screen until they executed a button press to toggle either forward or backward between images. The familiarization task ended when subjects had viewed all possible target images, and felt sufficiently familiar with them as to distinguish between the object categories.

2.2.3. Object-substitution masking (OSM) task

Once familiar with the target objects, subjects completed 12 runs of the object-substitution masking task, each comprising 144 trials. With three target types (including a blank target type - see below) and two masking conditions, this yielded a total of 288 trials per condition (e.g., 288 masked smoking-related target trials, and so on). Every trial began with a brief array, which included a single target, denoted by four small black squares at its corners, among 11 distracter images, three of which occupied the other possible target locations (Fig. 1). The remaining distracters were distributed as follows: two were presented above and below fixation, along the vertical meridian (centered 9.4 degrees from fixation); two were presented directly to the left and right of fixation (centered 8.6 degrees from fixation); and four were presented diagonally from fixation in each of the four quadrants (centered 13.5 degrees from fixation). Targets were presented in a spatially unpredictable fashion from trial to trial, and occurred in any one of the four quadrants 6.0 degrees away from fixation. Three target types were possible, with target-present trials showing target objects belonging to either the smoking-related or the office-related categories with which the participants had been familiarized. The third target type contained four-square cues but no object presented in the target location. This 'blank' condition served as a type of control trial, representing a condition against which target-present trials could be compared, in order to track target-related processes. The initial array was presented on every trial for a duration of 26 ms (two frames on a 75 Hz projector). For unmasked trials, this initial array was immediately followed by 500 ms of the fixation screen alone, whereas for masked trials, the four-square cue remained on the screen with the fixation cross during this 500 ms interval (Fig. 1). The inter-trial interval was randomly jittered between 700 and 900 ms. Subjects were instructed to categorize the stimulus at the target location as quickly and accurately as possible via button press as a smoking-related stimulus, an office-related stimulus, or an empty space containing no target. The mapping of the buttons to specific responses was counterbalanced across participants.

2.3. EEG acquisition

For each session, continuous EEG was recorded using a Neuroscan recording system (El Paso, TX, USA). The EEG cap (Easycap, Herrsching, Germany) contained 32 channels, with one placed below the left eye and referenced to the frontal channels (Fp1, Fp2) monitoring eye blinks. In addition, bipolar channels applied to the outer canthi were used to monitor horizontal eye movements. Data were referenced online to the right mastoid, sampled at a rate of 254 Hz, bandpass filtered online from DC to 50 Hz, and the impedance of each channel was maintained below 5 kOhms, excluding that of the right mastoid (< 2 kOhms). Subject behavior was additionally monitored using a closed-circuit video system.

2.4. Data analysis

2.4.1. Behavior and questionnaires

For the OSM task, mean accuracy and median RT (for correct responses) were submitted to 2 × 2 × 3 repeated-measures analyses of variance (ANOVAs) with the factors of craving (nicotine-deprived session versus sated session), masking condition (simultaneous versus delayed cue offset), and target type (smoking-related, office-related, and blank target trials). In addition, for target-present trials, measures of mean detection, detected target discriminability (d'), and response bias, were submitted to 2 × 2 × 2 ANOVAs with the factors of craving, masking, and target type. For the measure of response bias, the percent of true positive responses for detected targets of a given category (e.g., % office images correctly classified as 'office') was combined (summed) with the percent of false positive responses for that category (e.g., % smoking images erroneously categorized as 'office'). By subtracting the % detected for that trial type from this sum, an index of response bias for a given option was extracted, with a positive value reflecting a bias toward, a negative value reflecting a bias away, and a value of zero reflecting no response bias. The Questionnaire for Smoking Urges, which served as our measure of craving, comprises two factors that are viewed as largely independent (Cappelleri et al., 2007; Tiffany and Drobes, 1991). The first factor quantifies the more positive quality of craving, reflecting the anticipation of the pleasurable experience associated with smoking, whereas the second factor reflects the negative experience of craving, or, the anticipated alleviation of unpleasant feelings associated with deprivation. Each of these sets of factor values was submitted to a two-tailed *t*-test across session type (deprived versus non-deprived) to validate the induction of a craving state.

2.4.2. EEG

Following EEG acquisition, data contaminated by physiological artifacts (e.g., eye blinks) were identified and excluded using a peak-to-peak amplitude threshold algorithm, titrated on a subject-by-subject basis, and applied blindly within the peristimulus time window from −100 ms to +1000 ms. Subjects with a rejection rate exceeding 25% of all trials in either recording session were excluded from further analyses, resulting in the exclusion of 7 participants. For the remaining subjects, this process yielded a threshold range of 120–160 uV, as well as a mean rejection rate of 7.1%, which did not significantly differ across sessions (5.6% for non-craving, 8.5% for craving; $t_{21} = 1.96$, $p = .06$). Artifact-free data were time-locked averaged for each condition. Specifically, data were averaged according to stimulus condition (i.e., masked and unmasked trials containing smoking-related target objects, office-related target objects, and blank targets), as well as by behavior within the masked condition (correct and incorrect responses). These averages were then re-referenced to a common reference (i.e., referenced to the average of all channels), and filtered offline using a finite impulse response low-pass Gaussian filter with an edge frequency of approximately 23 Hz.

To isolate lateralized indices of attentional deployment and extended target processing reflected in the N2pc and in the sustained posterior contralateral negativity (SPCN), respectively, additional well-established analyses (Luck, 2005) were performed that flip channels about the midline with respect to the target. More specifically, difference waves were calculated to yield a 'contralateral minus ipsilateral' target subtraction. In this process, a 'contralateral target' response is extracted by combining data from right scalp sites for left-hemifield target trials, with left scalp site data for right-hemifield target trials that has been flipped about the midline, thereby placing the activity contralateral to the target on the right side of the scalp. Right scalp sites in this concatenated data thus represent all extracted evoked potentials contralateral to the hemifield in which a target was presented. Similarly, unflipped data from the right scalp site for right-hemifield trials is combined with hemisphere-flipped data for left hemifield trials to extract an 'ipsilateral target' response at the right scalp sites. Subtracting this ipsilateral target response from contralateral target responses yields the N2pc and SPCN components at right scalp electrodes (with the inverse of this, namely ipsilateral minus contralateral, displayed at the left scalp channels). The ERP traces from this manipulation, and the analyses of the N2pc and SPCN components from it, were extracted from right-hemisphere channel P4 (i.e., a flipped combined representation of data originally from P3/P4). For plotting and statistical purposes, a baseline of the pre-stimulus time window (i.e., between −100 and 0 ms relative to stimulus onset) was used. For behavioral and EEG measures, all repeated-measures ANOVA statistics reported are Greenhouse-Geisser corrected values, and all reported *t*-tests are two-tailed.

3. Results

3.1. Questionnaires

The participant sample reflected a broad range of nicotine-dependency levels. The Fagerstrom Test for Nicotine Dependence (FTND)

Table 1
Summary of behavioral results. The mean accuracy and median response time (for correct trials) are given for each trial type and masking condition. Values are collapsed across the factor of craving, as no significant behavioral effect for session type was observed. For target-present trials, mean detection rate, mean d', and mean response bias measures are given for each target type and masking condition, collapsed across the factor of craving, for which there were no observed effects. SE refers to the standard error of the mean.

Target type	Unmasked trials	Masked trials
	Mean accuracy (SE) %	**Mean accuracy (SE) %**
Office-related target	74 (2.2)	70 (2.5)
Smoking-related target	65 (3.6)	57 (4.0)
No-target (blank)	85 (2.7)	88 (2.0)
	Median RT (SE) ms	**Median RT (SE) ms**
Office-related target	637 (14.8)	640 (15.0)
Smoking-related target	641 (14.7)	642 (14.5)
No-target (blank)	594 (15.0)	590 (16.1)
	Mean detection (SE) %	**Mean detection (SE) %**
Office-related target	95 (1.0)	90 (2.3)
Smoking-related target	95 (1.0)	91 (2.5)
	Mean d' (SE)	**Mean d' (SE)**
Office-related target	1.25 (.10)	1.03 (.10)
Smoking-related target	1.37 (.10)	1.16 (.09)
	Response bias (SE) %	**Response bias (SE) %**
Office-related target	+ 8.9 (4.3)	+ 13.3 (3.9)
Smoking-related target	− 9.1 (5.4)	− 13.5 (5.5)

yielded an average value of 4.1, with individual scores ranging from 0 (very low) to 8 (very high), and a mean Heaviness of Smoking Index (HSI) of 2.7. In addition, the Questionnaire for Smoking Urges (QSU) administered at the beginning of both sessions showed that the deprivation period resulted in an increase of craving. This questionnaire comprises two factors, one positive and one negative, referring to the perceived outcomes of gaining access to a cigarette (i.e., the positive experience of smoking and the alleviation of the negative experience of deprivation). Both of these factors increased in the nicotine-deprived session relative to the non-deprived session. Specifically, the positive factor increased from 4.2 ($SE = .3$) in the non-deprived session to 5.9 ($SE = .3$) in the deprived session ($t_{21} = 6.6$, $p < .001$), while the negative factor increased from 2.0 ($SE = .2$) in the non-deprived session to 3.1 ($SE = .3$) in the deprived session ($t_{21} = 5.3$, $p < .001$).

3.2. Behavior

Measures of accuracy (Table 1, Fig. 2A), and response times (RTs; median for correct responses, Table 1, Fig. 2B) were submitted to repeated-measures analyses of variance (ANOVAs), with the factors of session type (craving versus non-craving), masking condition (unmasked versus masked trials), and target type (office supply targets, smoking targets, no-target trials). For accuracy, a main effect of masking ($F_{1,21} = 6.0$, $p < .05$, $\eta_p^2 = .223$) was observed, with the percent of correct responses falling from 75% in the unmasked condition to 72% in the masked condition (collapsed across all trial types). In addition, a main effect of target type was observed ($F_{2,42} = 26.1$, $p < .001$, $\eta_p^2 = .554$), with subjects being most accurate in responding to no-target trials (86%; $t_{21} = 4.7$, $p < .001$ as compared to office-supplies; $t_{21} = 8.9$, $p < .001$ as compared to smoking targets), followed by office-supply target trials (72%), and least accurate in responding to smoking-related target trials (61%; $t_{21} = 2.5$, $p < .05$ as compared to office targets). Finally, a significant masking by target-type interaction was observed ($F_{2,42} = 10{,}7$, $p < .01$, $\eta_p^2 = .338$). Follow-up tests revealed that this interaction was driven by greater disruption of accuracy by masking for smoking-related images relative to other target types. Specifically, while masking appeared to have no effect on response accuracy for no-target trials ($t_{21} = 1.3$, $p = .22$), smoking-related targets were more susceptible to the effects of masking than office-supply targets, with accuracy falling from 65% to 57% for smoking targets ($t_{21} = 6.6$, $p < .001$) and from 74% to 70% for office supply targets ($t_{21} = 2.3$, $p < .05$). Follow-up tests revealed that the magnitude of the masking effect for office targets differed significantly from that associated with smoking targets ($t_{21} = 2.5$, $p < .05$). Subjects easily identified non-target (i.e., blank) trials, and their accuracy was higher for no-target trials than for smoking-related targets and non-smoking targets within the unmasked ($t_{21} = 6.1$, $p < .001$; $t_{21} = 3.2$, $p < .01$) and masked condition ($t_{21} = 10.6$, $p < .001$; $t_{21} = 5.6$, $p < .001$). This result likely reflects the qualitatively distinct task inherent in no-target trials, which is to simply detect and report the absence of an object within the four-square cue. Finally, within the unmasked condition there was no significant difference in accuracy between smoking and non-smoking targets ($t_{21} = 1.9$, $p = .07$), while accuracy was significantly lower in response to smoking-related targets than to non-smoking targets within the masked condition ($t_{21} = 3.0$, $p < .01$). Overall, these results show that the substitution masking disrupted target-related processing, but in a manner that more greatly disrupted accuracy for smoking-relevant targets than for other, smoking-irrelevant targets.

RT measures submitted to an analogous ANOVA showed a main effect of target type ($F_{2,42} = 22.0$, $p < .001$, $\eta_p^2 = .507$), with participants responding significantly faster to no-target trials (592 ms) than to office supply targets (639 ms; $t_{21} = 5.1$, $p < .001$) and smoking targets (642 ms; $t_{21} = 5.7$, $p < .001$), with no difference in response times between office-related and smoking-related targets ($t_{21} = .42$, $p = .68$). This indicates that masking did not slow subjects, and that, in agreement with accuracy measures, detecting the absence of a target in the 'blank' trials was a simpler task than target category discrimination.

Measures of detection (Table 1, Fig. 2C), discriminability (d', Table 1, Fig. 2D), and response bias (Table 1, Fig. 2E) for target-present trials were submitted to a 2 × 2 × 2 ANOVA with the factors of craving, masking, and target type. For detection, only a main effect of masking was observed, with performance falling from 95% in the unmasked condition to 90% in the masked condition ($F_{1,21} = 8.4$, $p < .01$, $\eta_p^2 = .284$). Measures of d' revealed that smoking-related targets were slightly more discriminable than office targets, evident in a main effect of target ($F_{1,21} = 4.5$, $p < .05$, $\eta_p^2 = .176$). A main effect of masking showed that discriminability of both target types fell for masked trials ($F_{1,21} = 32.7$, $p < .001$, $\eta_p^2 = .609$). Importantly, no masking-by-target interaction was observed for d' measures, indicating that the relative discriminability of the two targets did not change with masking ($F_{1,21} = .82$, $p = .38$, $\eta_p^2 = .038$). Subjects showed an overall response bias toward 'office' and away from 'smoking', reflected in a main effect of target type ($F_{1,21} = 6.5$, $p < .05$, $\eta_p^2 = .236$). A significant masking-by-target type interaction indicates that this shift away from 'smoking' responses increased with masking ($F_{1,21} = 9.4$, $p < .01$, $\eta_p^2 = .308$). Follow-up tests revealed significant response bias differences between target categories within the masked condition ($t_{21} = 3.2$, $p < .005$), and across masking conditions for the smoking category ($t_{21} = 2.8$, $p < .05$). Overall, as targets became uniformly less detectable and less discriminable, subjects tended to shift responses away 'smoking.' No other main effects or interactions were observed for these target-present comparisons.

3.3. EEG

3.3.1. N2pc index of attentional deployment

The N2pc index of lateralized shifts of visual attention was extracted as the mean amplitude difference at posterior parietal sites between responses to contralateral targets and ipsilateral targets (displayed on the right scalp), during the 225–275 ms post-stimulus time window (Fig. 3A and B). These values were submitted to a repeated-measures ANOVA with the factors of session type (craving versus non-craving), masking (unmasked versus masked trials), and target type (office targets, smoking targets, and no-target trials). The N2pc mean amplitude showed a main effect of masking ($F_{1,21} = 26.9$, $p < .001$, $\eta_p^2 = .562$),

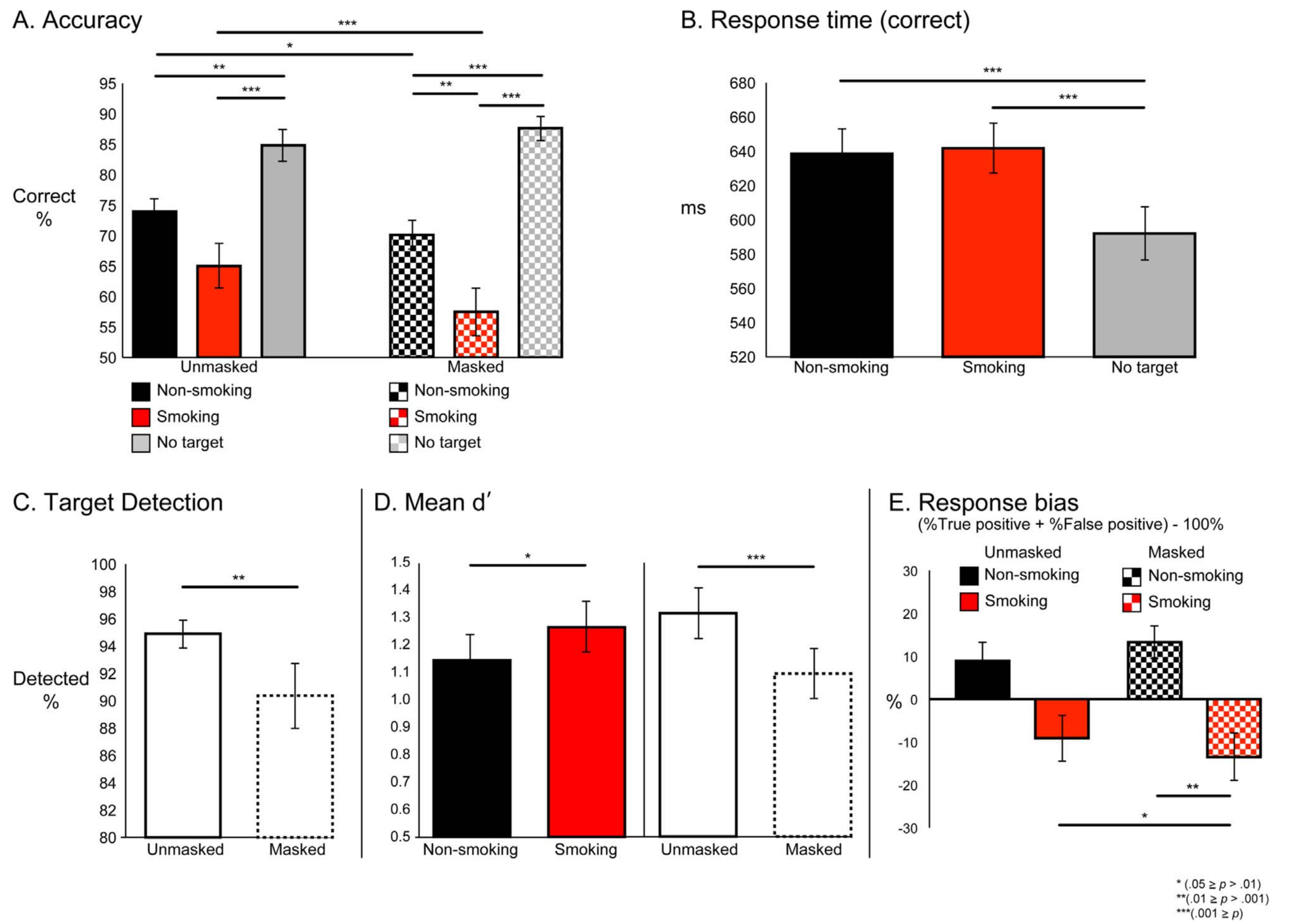

Fig. 2. Behavioral performance during object-substitution masking (OSM). A. Measures of mean accuracy showed reduced performance for target-present trials in the masked condition relative to the unmasked condition. A masking-by-stimulus interaction was observed, with accuracy being more greatly disrupted for smoking-related images than office-related images in the masked condition. Accuracy did not differ between smoking-related and office-related targets within the unmasked condition. Data are collapsed across session type, as no effects of craving were observed. B. Median response times for correct trials showed a main effect of stimulus, with target-present trials requiring more time than no-target (blank) trials. Response times did not differ between smoking-related and office-related trials. Data are collapsed across session type and masking, as no effects were observed for these factors. C. Mean detection rate for target-present trials. A main effect of masking was observed as an overall reduction in detection rate in the masked condition that did not differ between target categories. D. Left panel: mean d' values were significantly higher for smoking-related images relative to office images. Right panel: masking uniformly reduced target discriminability reflected in d' measures. No masking-by-target interaction was observed. E. Measures of response biases showed a main effect of target type, as well as a masking-by-target interaction, all driven by a response bias away from 'smoking' that became significant within masked trials.

being larger for masked trials than for unmasked trials (Fig. 3C). In addition, a significant masking by stimulus interaction was observed ($F_{2,42} = 25.9$, $p < .001$, $\eta_p^2 = .552$)(Fig. 3C). Subsequent tests revealed that while the N2pc to no-target trials remained unchanged across masking conditions ($t_{21} = .90$, $p = .38$), the amplitude of the N2pc in response to both office-supply-related and smoking-related targets were consistently higher in the masked relative to the unmasked condition ($t_{21} = 6.0$, $p < .001$ for office targets and $t_{21} = 6.8$, $p < .001$ for smoking targets). The masking by stimulus interaction therefore was driven by differences in the relative amplitude of the N2pc elicited by office targets and smoking targets across masking conditions. Specifically, although no significant difference in N2pc amplitude was observed between office and smoking targets for unmasked trials ($t_{21} = .35$, $p = .73$), masked smoking targets elicited a significantly larger N2pc than masked office targets ($t_{21} = 3.4$, $p < .01$). These findings demonstrate that the N2pc index of attentional shifting may not differentiate between object-categories in the unmasked condition, but in conditions of reduced perceptibility (i.e., masked trials), smoking-related images seem to capture visual attention more strongly than smoking-irrelevant ones (Fig. 3C).

An additional analysis of N2pc amplitude was conducted within the masked condition, with the factors of craving, behavioral performance (i.e., correctly identified versus incorrectly identified or missed targets), and target type (office target versus smoking-related target). This analysis revealed a main effect of target type, with masked smoking-related targets consistently eliciting a higher mean amplitude N2pc than office targets ($F_{1,21} = 6.5$, $p < .05$, $\eta_p^2 = .235$). No stimulus by behavior interaction was observed in the masked condition, indicating that this stimulus-driven effect on N2pc amplitude was not influenced by behavioral responses. No other main effects or interactions were observed.

3.3.2. Sustained posterior contralateral negativity (SPCN)

Like the N2pc, the longer-latency sustained posterior contralateral negativity (SPCN) was extracted via the contralateral minus ipsilateral subtraction, and displayed on the right scalp sites using the previously described channel flipping manipulation (Fig. 4A and B). Mean amplitude values during the post-stimulus time window of 500–800 ms were submitted to the analogous 3-factor repeated-measures ANOVA as done above for the N2pc. This analysis revealed a main effect of craving, with the SPCN being higher in amplitude during the craving session than during the sated session ($F_{1,21} = 14.5$, $p < .005$, $\eta_p^2 = .408$; Fig. 4 C). In addition, a main effect of masking was observed, with masked trials eliciting a higher amplitude SPCN than unmasked trials ($F_{1,21} = 43.8$, $p < .001$, $\eta_p^2 = .676$; Fig. 4 C). Finally, a main effect of target type ($F_{2,42} = 18.3$, $p < .001$, $\eta_p^2 = .466$) showed that no-target trials

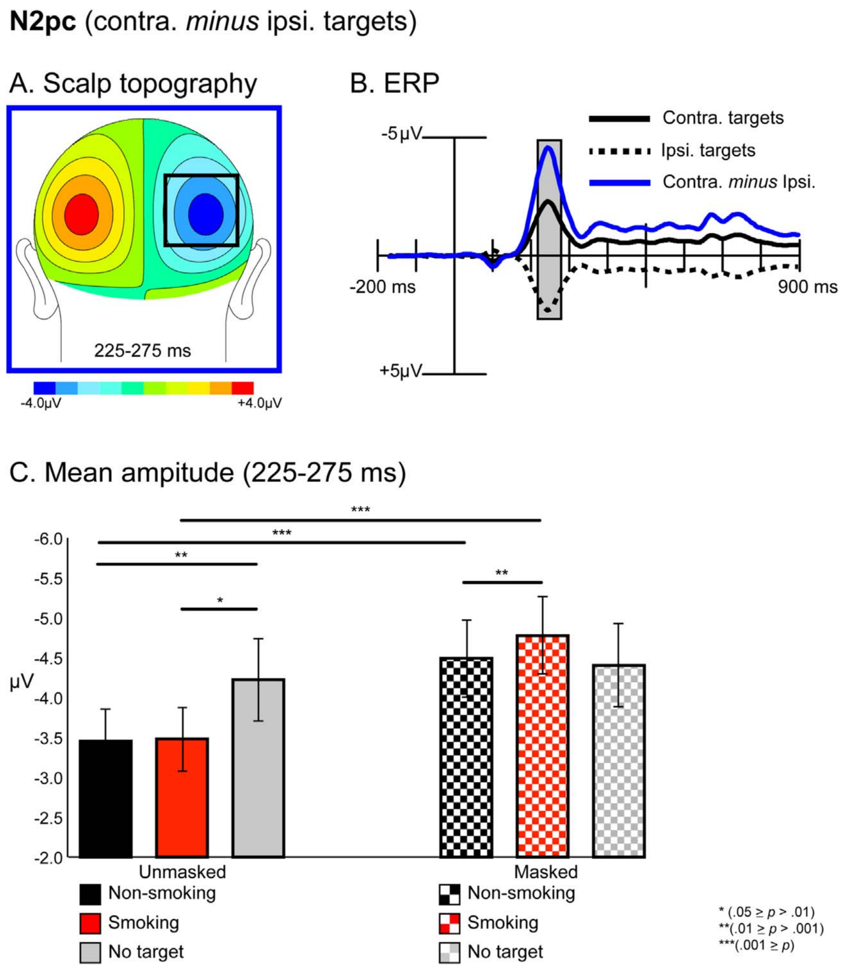

Fig. 3. N2pc extraction and observed effects of stimulus condition and masking. A. Scalp topography of the contralateral minus ipsilateral N2pc difference wave during the 225–275 ms post-stimulus time window (contra minus ipsi over the right hemisphere, ipsi minus contra over the left), with a parietal-occipital distribution. B. Extraction of the N2pc difference wave (blue), showing traces corresponding to contralateral targets (solid black trace) and ipsilateral targets (dashed black trace). N2pc peak and analysis time window, derived from this canonical N2pc, is highlighted in gray. C. Mean amplitude of the N2pc difference wave according to target type in unmasked conditions (left) and masked conditions (right), collapsed across craving and non-craving sessions. A stimulus-by-masking interaction was observed, driven by greater increase in amplitude of the N2pc in response to smoking-related targets relative to office-related targets in the masked condition relative to the unmasked condition. N2pc responses to no-target trials did not differ between masking conditions.

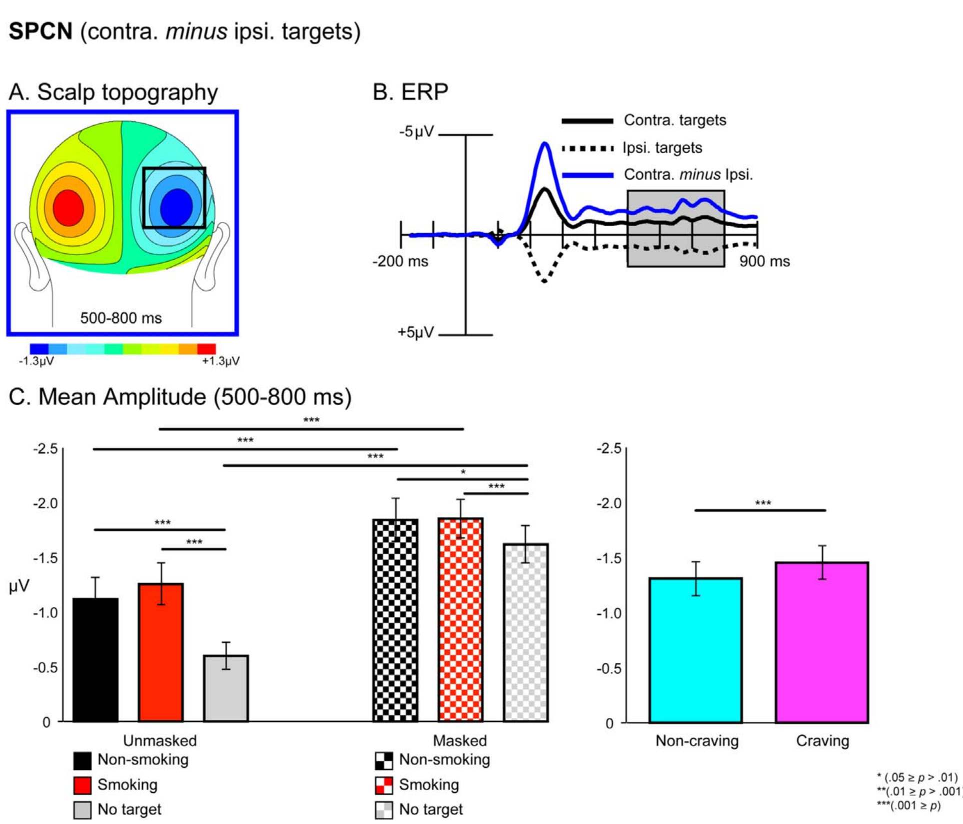

Fig. 4. Sustained posterior contralateral negativity (SPCN) extraction and observed effects. A. Scalp topography of the extracted contralateral minus ipsilateral SPCN difference wave during the 500–800 ms post-stimulus time window shows a posterior parietal-occipital distribution much like that of the N2pc. B. The extraction of the SPCN difference wave (blue trace) from a contralateral target (solid black trace) minus ipsilateral target (dashed black trace) subtraction. Mean amplitude values were extracted from the 500–800 ms post-stimulus time window. C. Repeated-measures ANOVA of mean SPCN amplitude with the factors session type (craving and non-craving), masking (masked and unmasked trials), and target type (smoking-related, office-related, and no-target trial) revealed main effects for all three factors, and no interactions. Mean SPCN amplitude was increased for craving sessions, masked trials, and target-present trials.

elicited a smaller SPCN than target-present trials ($t_{21} = 4.2$, $p < .001$ as compared to office targets and $t_{21} = 5.3$, $p < .001$ as compared to smoking targets; Fig. 4C). On the other hand, the SPCN in response to office-related and smoking-related targets did not differ ($t_{21} = 1.2$, $p = .23$). These results demonstrate that the SPCN seems to be subject to global effects of craving, masking, and the presence or absence of a target, while not showing the same distinctions between target types (i.e., smoking-relevant versus irrelevant) seen in the N2pc.

4. Discussion

4.1. Attentional capture by smoking-related content is automatic

The present study, through its manipulation of target perceptual visibility, underscores the complex dynamics of attentional capture by substance-related stimuli. Most importantly, it demonstrates that smoking-related images, when viewed by smokers under conditions of reduced visual awareness, capture attention more strongly than do non-smoking images, as reflected by the N2pc index of visual spatial attention.

This enhancement of the N2pc to smoking-related images in the masked condition, considered on its own, supports the independence of attentional allocation and the visual awareness processes disrupted by OSM (Harris et al., 2016; Woodman and Luck, 2003). In the special population represented by habitual smokers, patterns of previous results that are consistent with an attentional bias toward smoking-related stimuli seem to result from automatic processes. For example, the interference inherent in the Stroop task, which is enhanced when the task-irrelevant semantic content is smoking-related (Munafo et al., 2003), is likely a result of an automatic semantic analysis beyond the control of the viewer. In the case of the dot-probe paradigm, exogenous cueing by smoking-related stimuli likely results in the speeded responses observed for dots replacing smoking images (Ehrman et al., 2002; Waters et al., 2003). The automaticity of this process is also supported by its timing, being present in conditions with short cue-target onset asynchronies, but absent with longer SOAs (Chanon et al., 2010).

The present finding of automatic attentional capture reflected in the N2pc is accompanied by a parallel masking-by-stimulus interaction observed for behavioral measures of accuracy. Specifically, while attention appeared to be captured more strongly by smoking-related stimuli in the masked condition as reflected in the N2pc, accuracy was more reduced by masking for smoking-related stimuli than for non-smoking stimuli. This result appears counterintuitive, as it would be expected that greater attentional deployment reflected in the N2pc would result in improved target performance, especially when the relevant feature or object is embedded in the primary task. In the case of smokers, cued dot-probe studies examining target processing following the presentation of substance-related cues revealed faster behavioral responses to targets following a smoking-related stimulus (Ehrman et al., 2002; Waters et al., 2003). Similarly, in studies showing patterns of attentional avoidance of smoking stimuli embedded in an orthogonal task, weaker N2pc responses to targets containing a smoking-related image coincided with reduced behavioral performance (Donohue et al., 2016b), further supporting a link between the N2pc and behavioral performance.

To interpret the present findings, it is essential first to identify the attentional process the N2pc reflects in the present task. Spatial attention is an important factor in OSM, and the dynamics of attention to a target-plus-mask has implications for the N2pc, as well as for the efficacy of masking. Importantly, the relative weighting of attention toward the mask or target can either enhance or reduce the effects of masking. For example, previous research has demonstrated that increasing the salience of the four-element target-denoting cue can enhance the behavioral effects of substitution masking, which may also have implications for variations in the N2pc (Tata and Giaschi, 2004). In the same vein, other work has shown that pre-cueing attention to the target location reduces the effects of masking in OSM (Tata, 2002; Weidner, 2006). In contrast to these previous studies, our experiment equates the attentional status of the four-element target-denoting cue within each mask condition by providing no pre-cues to the target location, and by holding the asynchrony of the four-square cue onset and target onset constant at 0 ms for the different target types. Accordingly, although a general enhancement of the N2pc in the masked condition may reflect an increase in difficulty, any additional modulation of the N2pc related to target type, such as that presently observed, must be due to the unique attentional status of the target content, and not to that of the mask.

For the present study, behavioral measures of detection, and of detected-target discriminability reflected in mean d' values, are informative in further addressing this issue. Specifically, office and smoking targets were equally affected in their detectability and discriminability by masking, evident in the reported main effects. The seemingly increased disruption for smoking targets reflected in accuracy appears to be due to an increased response bias shift away from the 'smoking' response in the masked condition, evident in a parallel masking-by-target interaction for our index of response bias. In sum, it appears that the initial attentional capture reflected in the N2pc is a process that is distinguishable from the behavioral outcomes of the object-substitution masking, which supports the idea that attention is being captured in the absence of explicit target-content awareness. Put another way, in the masked condition, a visual feature of the targets identifying them as smoking- or office-related is distinguished by the visual system in a manner that results in early attentional capture reflected in the N2pc, but which does not reach full awareness and, in its perceived absence, results in the observed response bias away from smoking-related content.

4.2. A general effect of craving

Although craving did not appear to affect attentional-shifting processes reflected in the N2pc, our longer-latency measure of visual short-term memory and discrimination processes changed significantly as a function of target presence, masking, and craving. More specifically, the sustained posterior contralateral negativity (SPCN, latency 500–800 ms) was larger for trials containing targets vs. no targets, for masked trials vs. unmasked trials, and overall during the craving session vs. the non-craving one. The first two results are not particularly surprising, as the SPCN has previously been dissociated from attentional-shifting processes reflected in the N2pc and has been found to increase in amplitude along with task difficulty and working-memory load (Jolicoeur et al., 2008; Maheux and Jolicoeur, 2017; Prime et al., 2011). That it is also affected by the craving manipulation suggests that nicotine deprivation may increase task difficulty or overall arousal in a non-specific manner. This interpretation is corroborated by previous work showing an enhanced late frontal negativity likely reflecting cognitive-control processes in conditions of deprivation (vs. non-craving) in smokers who wished to quit (Donohue et al., 2016a). Moreover, under conditions of craving (vs. non-craving), smokers in a previous study from our group were found to have an enhanced sensory-evoked P1 response, again suggesting non-specific arousal under a state of nicotine deprivation (Donohue et al., 2016b).

The present experiment is complicated by the fact that it was not sensitive to measures of effortful suppression of smoking-related stimuli. Specifically, the smoking content of the stimuli was task-relevant, as the subjects were asked to categorize the target as smoking-related, office-related, or absent. Accordingly, under conditions of perceptual awareness, the suppression of smoking-related content was not incentivized, nor was an attentional bias toward such content. This seems to result in no attentional bias measured neurally or behaviorally in the unmasked condition, with the N2pc, SPCN, detectability, and accuracy not differing in that condition for smoking-related versus office-related targets. If the smoking-related content was in fact orthogonal to the primary task, it is possible that, in the unmasked condition, targets containing smoking-related content would be actively suppressed, resulting in a decrease in detection or accuracy in a primary task as a result of this suppression. Such a finding, coupled with the failure of this suppression in the masked condition, would further support the present interpretation, and would be consistent with studies showing that, when the smoking content of the target is task-irrelevant, smokers tend to avoid attending to it (Donohue et al., 2016b).

In addition, although the present study extracted effects that are downstream of (i.e., later than) initial attentional capture, and that appear sensitive to the manipulation of craving (i.e., the SPCN measure of longer-latency target-discrimination processes), we did not probe specific measures of cognitive control and effortful suppression of smoking-related content, the failure of which may have given rise to the attentional capture observed in the masked condition. Follow-up studies specifically isolating mechanisms and measures of cognitive control under conditions of reduced awareness and task-irrelevance of smoking content would therefore be necessary to more definitively address these issues. Finally, the present study examined attentional capture by smoking-related stimuli in smokers that, while habitual in their nicotine consumption, exhibited relatively low heaviness of smoking indices (HSI). It is possible that the state of craving may significantly influence the automaticity of attentional capture by smoking-related content in especially heavy smokers, and this issue merits further investigation.

4.3. Conclusions

The influence of substance-related stimuli on visual attention is a complex phenomenon that can entail both enhancements and impairments of both attentional capture and behavioral facilitation, depending on the task and circumstance. In the case of smokers, this influence has implications for cessation success, and the depth with which it operates is a significant avenue of research. The present study contributes to this field by demonstrating the automaticity of attentional capture by smoking-related stimuli in smokers using object-substitution masking in conjunction with ERP measures of visual attentional processes. This automatic effect of attentional capture appears to be in opposition to effortful processes that otherwise regulate attentional deployment and achieve desired behavioral performance. Importantly, craving does not appear to interact with this process, though it does result in global changes in late visual cognitive processes similar to the effects seen with increased task demand and arousal. Given the sheer volume of visual information we are continually confronted with in the real world, as well as the extent to which undetected stimuli are processed and could influence behavior, attentional capture by unseen smoking-related stimuli is likely among the confluence of forces driving the maintenance or cessation of smoking behavior.

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