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ORIGINAL INVESTIGATION

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Discriminative stimuli that control instrumental tobacco-seeking by human smokers also command selective attention

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Abstract *Rationale:* Incentive salience theory states that acquired bias in selective attention for stimuli associated with tobacco-smoke reinforcement controls the selective performance of tobacco-seeking and tobacco-taking behaviour. *Objectives:* To support this theory, we assessed whether a stimulus that had acquired control of a tobacco-seeking response in a discrimination procedure would command the focus of visual attention in a subsequent test phase. *Methods:* Smokers received discrimination training in which an instrumental key-press response was followed by tobacco-smoke reinforcement when one visual discriminative stimulus (S+) was present, but not when another stimulus (S−) was present. The skin conductance response to the S+ and S− assessed whether Pavlovian conditioning to the S+ had taken place. In a subsequent test phase, the S+ and S− were presented in the dot-probe task and the allocation of the focus of visual attention to these stimuli was measured. *Results:* Participants learned to perform the instrumental tobacco-seeking response selectively in the presence of the S+ relative to the S−, and showed a greater skin conductance response to the S+ than the S−. In the subsequent test phase, participants allocated the focus of visual attention to the S+ in preference to the S−. Correlation analysis revealed that the visual attentional bias for the S+ was positively associated with the number of times the S+ had been paired with tobacco-smoke in training, the skin conductance response to the S+ and with subjective craving to smoke. Furthermore, increased exposure to tobacco-smoke in the natural environment was associated with reduced discrimination learning. *Conclusions:* These data demonstrate that discriminative stimuli that signal that tobacco-smoke reinforcement is available acquire the capacity to command selective attentional and elicit instrumental tobacco-seeking behaviour.

Keywords Incentive · Salience · Smoking · Cue-reactivity

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Introduction

According to incentive salience theory (Sokolov 1963; Bindra 1978; Robinson and Berridge 1993), Pavlovian contingencies between stimuli (S+) and drug reinforcement endow S+ with the capacity to command attention and this conditioned modification of selective attention controls the selective performance of drug-seeking and drug-taking behaviour. The main appeal of this theory is economy—associative learning needs only alter selective attention in order to influence the behavioural output of the agent.

Evidence for incentive salience learning in human tobacco-addiction comes from studies that have measured smokers' attentional response to smoking-related cues (pictures of cigarettes, smoking related words or scripts, for example) versus neutral control cues (pictures of pencils, control words or scripts, for example). Such studies have shown that smokers are slower to name the ink colour of smoking-related words than that of neutral control words in the Stroop task (Gross et al. 1993; Waters and Feyerabend 2000). Similarly, presentation of smoking cues slow smokers' reaction times for targets (Sayette and Hufford 1994; Baxter and Hinson 2001), and reduce smokers' comprehension of demanding linguistic material (Zwaan and Truitt 1998; Zwaan et al. 2000; Madden and Zwaan 2001) relative to control conditions. These findings demonstrate that smoking cues command limited processing resources, and thereby reduce the processing resources available for other behavioural operations.

Other studies have measured the command of processing resources by smoking cues more directly. Jarvik et al. (1995) reported that smokers identify smoking words more quickly and accurately than neutral words, whereas Rosenblatt et al. (1996) found superior recognition memory for smoking-related images compared to control images. More recently, the dot-probe task has been used to demonstrate that smokers allocate the focus of visual attention to smoking-related stimuli presented briefly in the periphery of the visual field in preference to control stimuli (Ehrman et al. 2002; Mogg and Bradley 2002; Bradley et al. 2003; Hogarth et al. 2003).

According to incentive salience theory, smoking-related cues acquire the capacity to command attention through Pavlovian conditioning with tobacco-smoke reinforcement. In the present study, we assessed this hypothesis directly by associating in the laboratory, one neutral stimulus with tobacco-smoke reinforcement and another neutral stimulus with the absence of tobacco-smoke reinforcement, and then tested the capacity of these two stimuli to command attention.

In the natural environment, Pavlovian contingencies between stimuli and tobacco-smoke reinforcement are probably embedded within discriminative instrumental contingencies, where the smoking cues signal when instrumental tobacco-seeking behaviour will yield tobacco-smoke reinforcement (see Colwill and Rescorla 1988). For this reason, we employed a discriminative instrumental conditioning procedure in which one visual discriminative stimulus (the S+) signalled that a key-press response (the instrumental tobacco-seeking response) would elicit instructions to take up to two puffs on a cigarette, whereas another visual discriminative stimulus (the S−) signalled that the same key-press response would elicit instructions to blow into a breath carbon monoxide (CO) monitor (which controlled for the action that followed the S+ without reinforcement). It was expected that during training participants would learn to perform the key-press response in S+ trials selectively, relative to S− trials, demonstrating that the S+ had acquired control of the instrumental tobacco-seeking response. According to incentive salience theory, the S+ will acquire the capacity to control the instrumental tobacco-seeking response and the capacity to command attention, simultaneously.

Stimulus control of tobacco addiction has been demonstrated previously, most notably by Perkins et al. (1994), who found that a lit cigarette caused smokers to increase their response rate for tobacco-smoke reinforcement in a variable ratio schedule, and by Mucha et al. (1998), who found that a smoking paired S+ increased the time smokers spent puffing on a cigarette. Other studies have demonstrated that smoking-related cues or smoking-paired contexts increase human smoking topography relative to control conditions (Herman 1974; Glad and Adesso 1976; Suraway et al. 1985; Payne et al. 1990, 1991; Niaura et al. 1992; Droungas et al. 1995).

The skin conductance response to the S+ and S− were measured in training to provide independent evidence that the discriminative instrumental contingencies did in fact bring about Pavlovian conditioning to the S+ (Dawson and Schell 1982; Field and Duka 2002).

The dot-probe task was used in the present study to determine whether the S+ established in discrimination training would command the focus of visual attention to a greater extent than the S−. Such differential attentional control by the S+ and S− could be attributed to the differential associative strength that these two stimuli had acquired with tobacco-smoke reinforcement during discrimination training. The dot-probe task was used to test the differential attentional control of the S+ and S− because this procedure has been validated previously as a measure of the command of selective visual attention by salient stimuli presented in competition with control stimuli (Posner et al. 1980; MacLeod et al. 1986; Mogg et al. 1998; Lubman et al. 2000; Townshend and Duka 2001; Ehrman et al. 2002; Mogg and Bradley 2002; Bradley et al. 2003; Hogarth et al. 2003). In the dot-probe task of the present study, the S+ and S− were briefly presented simultaneously in separate lateral position of the peripheral visual field (left and right of fixation) followed by a dot-probe in one of these positions, to which participants responded manually as quickly as possible. Faster reaction times for dot-probes in the same position as the S+ relative to dot-probes in the same position as the S− would reveal that the S+ had acquired the capacity to command the focus of selective visual attention to a greater extent than the S−, as anticipated by incentive salience theory.

In summary, the main predictions of the study were that smokers would learn to perform the instrumental tobacco-seeking response selectively in the presence of the S+ relative to the S−, that the S+ would elicit a greater skin conductance response than the S−, and that dot-probes in the same position as the S+ would be detected more rapidly than dot-probes in the same position as the S−. It should be noted at this stage that these differential instrumental, skin conductance and attentional responses elicited by the S+ versus S− would probably be due to an amalgam of the excitatory association between the S+ and tobacco-smoke reinforcement and the inhibitory association between the S− and tobacco-smoke reinforcement (Dickinson and Dearing 1979). The independent contribution of the excitatory and inhibitory process to the response measures cannot be isolated with the present design.

Individual differences in extra-experimental exposure to tobacco-smoke were estimated with questionnaires, to determine if this factor would influence the three main dependent variables of the study: discrimination performance, the skin conductance response to the S+ and the attentional bias for the S+. In addition, subjective craving to smoke was recorded prior to training and testing and correlated with the indices of the vigour of the tobacco-seeking response (Carter and Tiffany 2001), the skin conductance response to the S+ and the attentional bias for the S+. Finally, the attentional bias for the S+ was examined in relation to the number of times the S+ was paired with tobacco-smoke in training, and the skin conductance response to the S+.

Materials and methods

Participants

The experiment was completed by 32 smokers who were recruited from the student population at the University of Sussex. During recruitment, participants were asked to abstain from smoking during the morning prior to the experiment to induce a roughly uniform high motivation to smoke at arrival. All participants had 20:20 or 20:30 vision and gave informed consent. The University of Sussex ethics committee approved the study. Four participants were excluded from the study for reasons that will be described in the results section. The characteristics of the remaining 28 smokers are shown in Table 1.

Apparatus

The four greyscale spatial gratings shown in Fig. 1 were displayed on a 17-inch Viglen Trinitron colour monitor at a size of 10.2 cm squared. All other screen stimuli were black on a grey background. Stimulus presentation and response collection were controlled by a Pentium PC running Micro Experimental Laboratory software connected to a five-key response box with a light above each key (Psychology Software Tools, Inc: http://pstnet.com). A separate PC sampled skin conductance in micro siemens once per second through silver-silver chloride electrodes connected to the left small and middle finger. Med Associated Inc. (http://med-associates.com/

Table 1 Characteristics of smokers included in the analysis and of sub-categories based upon gender and cigarettes smoked per day

Characteristic		Smokers (n=28)	Male smokers (n=13)	Female smokers (n=15)	Group effect	Light smokers (n=23)	Heavy smokers (n=5)	Group effect
Sex ratio	Males	13	13	0	–	10	3	Fisher's P>0.05
	Females	15	0	15	–	13	2	
Number of cigarettes smoked per day	Mean	14	14.6	13.5	t(26)=0.5, P>0.05	12.4	21.5	–
	SD	5	5.1	5.2		3.9	2.2	
	Min	3	7.5	3		3	20	
	Max	25	25	22.5		17.5	25	
Years spent smoking	Mean	6	6.7	5.3	U=65.5, P>0.05	5.1	9.8	U=21, P>0.05
	SD	3.6	3.7	3.5		3	4.3	
	Min	1	2	1		1	4	
	Max	14	14	14		13	14	
Fagerstrom tolerance questionnaire score	Mean	4.2	4.4	4.1	U=97.5, 0.05	3.6	7	U=12, P>0.01
	SD	2.1	2.4	1.8		1.4	2.5	
	Min	1	2	1		1	4	
	Max	10	10	9		7	10	
Time since a cigarette (h)	Mean	11.3	11.3	11.3	t(26)=0.04, P>0.05	11.6	10.2	t(26)=1.52, P>0.05
	SD	1.9	2.4	1.3		1.9	1.6	
	Min	8	8	9.5		8.5	8.0	
	Max	17	17	13.5		17	12.5	
Years of age	Mean	21.9	22.7	21.2	U=85.5, P>0.05	21.2	25.2	U=17, P>0.05
	SD	3.6	4.6	2.4		3.2	3.8	
	Min	18	18	19		18	22	
	Max	31	31	27		31	31	
QSU-brief score obtained prior to training	Mean	4.3	4.5	4.1	t(26)=1.00, P>0.05	4.1	5.2	t(26)=2.10, P>0.05
	SD	1.1	1.1	1.2		1.1	.8	
	Min	1.6	2.4	1.6		1.6	4.0	
	Max	6	6	5.7		5.8	6.0	
QSU-brief score obtained prior to testing	Mean	4.3	4.5	4.2	t(26)=0.85, P>0.05	4.2	4.9	U=32, P>0.05
	SD	1.1	1.2	1		1.1	0.9	
	Min	2.4	2.6	2.4		2.4	3.4	
	Max	6.3	6.3	6.1		6.3	5.8	
Breath CO measured prior to training	Mean	9.2	12.5	6.3	U=59.5, P>0.05	7.1	18.8	U=15, P>0.05
	SD	7.7	9.9	3.4		5.1	10.7	
	Min	2	2	2		2	7	
	Max	36	36	15		22	36	
Breath CO measured after to training	Mean	20.2	21.5	19	t(26)=0.73, P>0.05	18.3	29	t(26)=2.65, P>0.05
	SD	9.1	10.4	8		8.5	6.4	
	Min	5	5	7		5	24	
	Max	40	40	34		34	40	
Breath CO measured prior to testing	Mean	12.7	14.4	11.2	t(26)=1.76, P>0.05	11.7	17.4	t(26)=2.58, P>0.05
	SD	5	5.5	4		4.6	4.2	
	Min	5	6	5		5	13	
	Max	22	22	20		20	22	

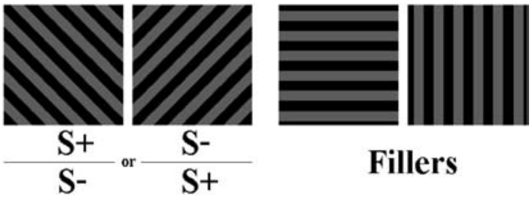


Fig. 1 Stimuli used in the experiment (not to scale). The horizontal and vertical oblique spatial gratings were presented in the dot-probe filler task in training and in filler trials in testing. The left and right oblique spatial gratings were counterbalanced between-participants in the role of S+ and S− in conditioning trials in training

index.htm) skin prep fluid (TD-260) and electrode paste (TD-246) were employed.

Participants were seated at a table that supported two grey metal boxes 27 cm squared by 15 cm high, 38 cm apart. Boxes could be opened by a handle on their front surface to reveal their contents. The "smoke box" contained a green glass cup containing ten of participants' preferred cigarettes, a lighter and ashtray, and was ventilated so that lit cigarettes contained inside could not be detected from the room. The "blow box" contained a Bedfont Scientific Ltd piCO Smokerlyzer breath CO monitor (http://bedfont.com).

Questionnaires

Tobacco-smoke exposure

Participants' lifetime exposure to tobacco-smoke was estimated from the number of cigarettes typically smoked per day, the number of years spent smoking and from Fagerstrom tolerance questionnaire scores (FTQ; Fagerstrom and Schneider 1989). The FTQ contained three items related to smokers' exposure to tobacco-smoke/nicotine and five items related to smokers' inability to refrain from smoking. The FTQ yields a composite score ranging from 0 to 11, where greater scores indicate greater tobacco exposure/dependence.

Subjective craving to smoke

The 10-item version of Tiffany and Drobes (1991) questionnaire of smoking urges, the QSU-brief (Cox et al. 2001), was used to measure craving. This questionnaire yields two factors, which were collapsed because no differential relationships were found between these factors and the main dependent variables of the study.

Contingency awareness

We wished to ensure that all participants developed the capacity to verbalise the stimulus-outcome contingencies in training, to avoid a post-hoc between-participants factor that often complicates human conditioning studies (Lovibond and Shanks 2002). To achieve this end, a contingency awareness test was administered, on paper, which showed the S+ and S−, and which asked participants whether they were allowed to smoke or blow during the presentation of each stimulus; a yes/no answer was given. Participants were scored as contingency aware if they answered all four questions correctly. This test was administered half way through training, to prompt attention to the stimulus-outcome contingencies in the remaining half of training, after training, to ensure participants were contingency aware prior to the test phase, and after testing, to determine whether contingency awareness had been retained over the interval.

Procedure

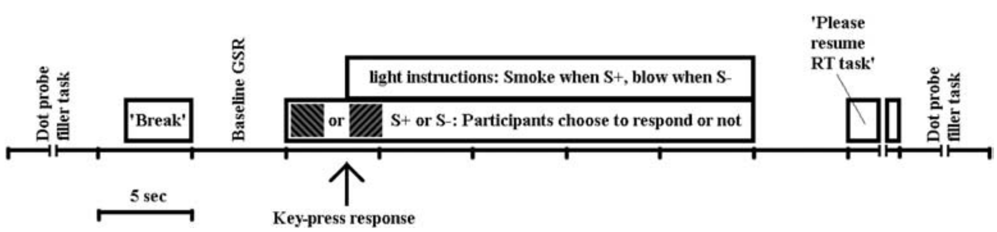
The study commenced at 10:00 or 12:00 hours with a 2-h training phase, which began with the measurement of 3-m Snellen visual acuity, followed by breath CO and questionnaires of informed consent, age, sex, tobacco-smoke exposure and time since a cigarette. Craving was then measured in the testing room prior to the first discrimination training session, which was followed by a 15-min rest period during which the contingency awareness test was administered. The second discrimination training session was then completed followed by the second test of contingency awareness and breath CO. Participants were then instructed to abstain from smoking during the 2 h that followed, which were spent outside the laboratory. Upon participants' return for the 1-h test phase, breath CO was recorded. Then craving was measured in the testing room before completion of the dot-probe task, which was followed by the third test of contingency awareness. The dot-probe task lasted approximately 40 min and the test phase lasted 1 h. The experiment lasted 5 h and ended with the payment of £20.

Discrimination training

Participants completed two discrimination training sessions, each of which lasted approximately 35 min. Each session comprised 20 blocks of a dot-probe filler task, which used the filler stimuli shown in Fig. 1, and 20 interleaved conditioning trials, which used the S+ and S− shown in Fig. 1. Each conditioning trial lasted 38 s, as shown in Fig. 2, and was separated from the conditioning trial that followed by a block of the dot-probe filler task, which lasted approximately 1 min. This 1-min gap between conditioning trials was designed to ensure that phasic increases in plasma nicotine obtained during an S+ conditioning trial did not overlap with the stimulus (S+ or S−) presented in the next conditioning trial. The period of one minute was selected on the basis of Isaac and Rand (1969), who found that phasic increases in plasma nicotine obtained from cigarette puffs decreased to baseline within 30 s. Consequently, we expect the S+ to be associated with phasic increases in plasma nicotine, and the S− to be associated with baseline plasma nicotine and/or the absence of a phasic increase in plasma nicotine.

The first discrimination training session began with a practice block of the dot-probe filler task, which was introduced with screen text instructions. These instructions described the stimulus sequence and response requirements of the dot-probe task, and participants were asked to look at fixation crosses. The practice block comprised eight trials, each of which began with central fixation cross presented for 1000 ms, followed by the horizontal and vertical spatial gratings shown in Fig. 1, presented as a pair for 500 ms, 8.75 cm to the left and right of the centre of the screen. Participants sat unrestrained 100 cm from the screen, creating 5

Fig. 2 The arrangement of conditioning trials interleaved with blocks of the dot-probe filler task in training



degrees of visual angle between the centre of the screen and the centre of either stimulus. Upon the offset of each picture pair, a dot-probe appeared in the centre of the position occupied by one stimulus (left or right) and participants responded as quickly as possible with their left or right forefinger upon the left or right response key, corresponding to the side of the probe, as quickly as possible, whilst avoiding mistakes. The feedback text, "correct" or "incorrect" was presented for 750 ms after key presses to signal whether each response accurately corresponded to the side of the probe. An inter-trial-interval (ITI) of 750 ms, 1000 ms, 1250 ms or 1500 ms then elapsed prior to the start of the next trial. The position of the horizontal and vertical grating (left, right) and the position of the dot-probe (left, right) were randomised across the eight trials. Subsequent blocks of the dot-probe task omitted the feedback.

After the practice block, the first conditioning trial was introduced with screen text instructions that informed participants that a 40-s break would follow each block of the dot-probe filler task and that one of two stimuli would be presented during each break. These two stimuli (the S+ and S−) were then viewed briefly in order that the difference between them might be discerned. Participants were then instructed that if they wished to smoke in the breaks they should press the middle key of the response box while the stimulus was present, that this middle key-press response would cause a light to appear on either the left or right side of the response box and that the grey box on the same side as the light was to be opened. Participants were further instructed that if the box contained cigarettes (the "smoke box") they were to light one and inhale once or twice but no more, then place the cigarette in the ashtray (still lit) and close the box, but if the box contained the CO monitor (the "blow box") they were to take a deep breath and breath in to it, then replace the monitor and close the box. Following these instructions, participants pressed the left or right key to initiate the first conditioning trial.

Conditioning trials began with the word 'break' presented centrally for 3000 ms, as shown in Fig. 2. In the 5 s that followed, a grey screen was presented and baseline skin conductance was recorded. The S+ or the S− was then presented centrally for 25 s and the skin conductance response to the stimulus was recorded. During stimulus presentation, participants chose to press the middle key of the response box or not. In the presence of the S+, the key-press response illuminated the light on the response box that was on the same side as the smoke box. In the presence of the S−, the key-press response illuminated the light on the same side as the blow box. Participants knew from prior instructions that they should open the box and perform the action required. Stimulus offset, at the end of 25 s, was followed by a grey screen for 5 s and then instructions stating: "Please resume the reaction time task now, by pressing the left or right key." A key press produced a 1500 ms grey screen followed by the next block of the dot-probe filler task. During the first two conditioning trials, in which presentation of the S+ and S− was counterbalanced, the experimenter prompted participants to press the middle key and the screen text instructions mentioned earlier were read out as the relevant procedures unfolded. At the end of the second conditioning trial participants were told: "It is important to understand that you do not have to press the middle key in every trial if you do not wish to. If you do press the middle key you must always open the box and perform the action instructed by the light". Subsequent performance was video recorded to ensure correct execution of the procedure. Across the 20 conditioning trials in each training session, the left and right oblique spatial gratings shown in Fig. 1 were presented 10 times each in a pseudo-random order, ensuring that the same stimulus was not presented more than three trials in a row: L, R, L, R, R, R, L, R, L, R, R, L, L, L, R, R, L, L, R, L (L=left oblique grating, R=right oblique grating). This pseudo-random order was counter-balanced between-participants within each session, and within-participants between each session. The position (left, right) of the smoke and blow box and the side of the light (left, right) that illuminated in response to a key press in the presence of each stimulus, was counterbalanced between-participants. Consequently, the stimulus that played the role of S+ and S− was counterbalanced between participants. The instructions present at the start of session 1 were omitted in session 2, and instead, participants were told that the task was the same as the one they had completed previously.

Testing

In testing, the table was arranged in the same way as in training except that the smoke and blow boxes were empty. Participant were not informed that the smoke and blow outcomes were unavailable and the boxes were closed. Participants were told verbally: "this task is the same as the one you have just done". However, the test procedure was actually identical to the dot-probe filler task in training, with a number of modifications: there were greater trials per block, the S+ and S− stimuli were presented in the place of the filler stimuli in half of trials, there were no conditioning trials, and the middle key-press response (the tobacco-seeking response) was ineffective. Breaks were provided between blocks but these did not resemble the conditioning trials in training. Presumably, at some point in the test procedure participants learned that there were no conditions in which the middle key-press response could be produced.

The test procedure began with screen text instructions stating: "Press the left or right key to begin". A response initiated 388 trials of the dot-probe task. The first four trials presented the filler stimuli to provide a buffer zone in which RTs could stabilise before 384 trials proper. These 384 trials were sectioned by short breaks into six blocks of 64 trials. Breaks were signalled by the text: "Please take a short break. Press the left or right key when ready to resume." The 64 trials in each block were sectioned into four identical cycles of 16 trials. Each cycle contained eight trials in which the S+ and S− were presented and eight trials in which filler stimuli were presented. Within each cycle, the factors trial type (experimental, filler), picture location (left, right) and probe location (left, right) were randomised. RTs for dot-probes were collected for analysis.

Data analysis

Discrimination training

The number of conditioning trials in which participants performed the key-press response was summed for each level of stimulus (S+, S−) and training session (1, 2); the maximum number in each cell is 10. These data were entered into ANOVA. For the purpose of correlation analysis, discrimination scores were calculated by subtracting the number of S− trials in the key-press response was produced from the number of S+ trials in which this response was produced, for training session 1 and 2. Positive discrimination scores indicate the extent to which the key-press response was produced in S+ trials selectively.

Skin conductance

In conditioning trials in which the key-press response occurred, the skin conductance response to the S+ and S− was confounded with the smoke or blow outcome. We expected to obtain unconfounded skin conductance responses to stimuli from conditioning trials late in training when smoking satiation had resulted in the key-press response being withheld. In addition, the conditioned skin conductance response to the S+ was expected to manifest only at the end of training. For these two reasons, skin conductance data were selected for analysis from the final five S+ and S− trials in training, in which the key-press response was not produced.

Only 18 participants withheld at least one key-press response in both the final five S+ and S− trials, and so analysis of skin conductance data has an *n* of 18. These 18 participants withheld the key-press response in an average of 2.2 S+ trials and 3.6 S− trials. From these trials, a mean skin conductance response to the S+ and S− was calculated. Mean baseline scores calculated from equivalent trials were subtracted to reduce variability between-participants. The resulting scores were entered into ANOVA.

Testing

Error scores from the 192 experimental trials in testing were calculated by summing the number of trials in which the incorrect key was pressed, or in which an RT less than 100 ms or greater than 1000 ms was produced and expressing this sum as a percentage of the total number of experimental trials (this score is presented in participant exclusions below). Trials that contributed to error scores were excluded from the analysis of the attentional bias for the S+. Median RTs were calculated from experimental trials in testing with respect to the variables dot-probe location (same as the S+, same as the S−) and testing block (6). These data were entered into ANOVA. For correlation analysis, attentional bias scores were calculated by subtracting the median RT for dot-probes in the same position as the S+ from the median RT for dot-probes in the same position as the S−. Positive bias scores indicate in ms a speeding of RTs for dot-probes in the same position as the S+ over the S−, and estimate the extent to which the attentional focus was biased towards the S+ over the S−.

Gender variable

The gender variable was included in analysis of the three dependent variables of the study. Where no significant main effects or interactions were found with this factor, the analysis was repeated without this factor, for presentation.

Results

Participant exclusions

Two participants were excluded because their breath CO decreased by 1 part per million (ppm) over training, indicating a lack of smoke exposure (the breath CO of other participants is described below). One participant was excluded for smoking less than two cigarettes per day—the lower limit for inclusion set in our previous study (Hogarth et al. 2003). After these exclusions, one participant was found to have an error score in testing of 11.4%. This score was outlying in a box and whisker plot from the rest of the sample and so the participant was excluded. The 28 participants remaining after these exclusions had a mean error score in testing of 1.5% (SD: 1.4%, min: 0%, max: 4.6%, *n*: 28).

Breath CO

Participants' average breath CO was 9.2 ppm at the start of the experiment (see Table 1), and had increased to 20.2 ppm by the end of training. This increase was found to be reliable [$t(27)=-9.46$, $P<0.001$]. The 2 h of abstinence resulted in a drop in breath CO to an average of 12.7 ppm just before testing and this decrease from the end of training was significant [$t(27)=6.65$, $P>0.001$].

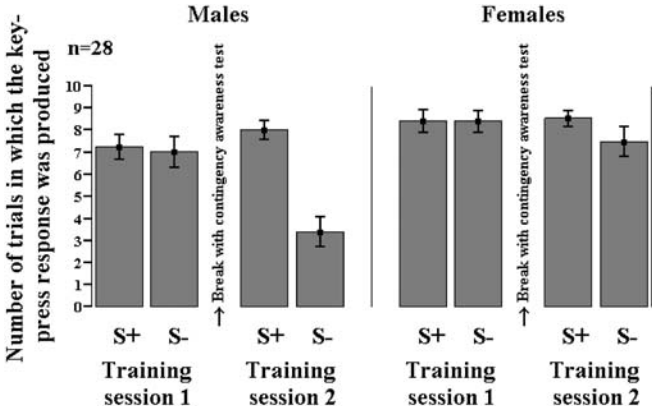


Fig. 3 The mean number of S+ and S− trials (±SEM) in which the key-press response (the instrumental tobacco-seeking response) was produced in training session 1 and 2 by males and females

Contingency awareness

The four questions of the contingency awareness test were answered correctly by six of the 28 participants at the end of training session 1, and by 25 of the 28 participants at the end of training session 2. The three participants who lacked contingency awareness at the end of training session 2 completed a third training session identical to the second, and acquired contingency awareness as a consequence. The second and third training session completed by these three participants were treated as the first and second training session respectively. The reliability of the reported contrasts, when assessed against $P\leq 0.05$, did not vary as a consequence of the inclusion or exclusion of these three participants.

Discrimination training

Figure 3 shows the mean number of S+ and S− trials in which the key-press response was produced, in training session 1 and 2, by male and female participants. Analysis of these data yielded a significant main effect of session [$F(1,26)=4.62$, $P=0.05$], a significant main effect of stimulus [$F(1,26)=31.55$, $P<0.001$], and a significant interaction between stimulus and session [$F(1,26)=40.76$, $P<0.001$], indicating that discriminative stimuli acquired control of the key-press response during training. Furthermore, there was a significant main effect of gender [$F(1,26)=9.54$, $P=0.005$], a significant interaction between stimulus and gender [$F(1,26)=12.89$, $P=0.001$], and a significant interaction between stimulus, session and gender [$F(1,26)=15.10$, $P=0.001$]. In males, the interaction between stimulus and session was significant [$F(1,12)=42.19$, $P<0.001$], whereas in females, this interaction was marginal [$F(1,14)=3.92$, $P=0.068$], indicating that the development of the expression of discrimination learning was more apparent in males than females.

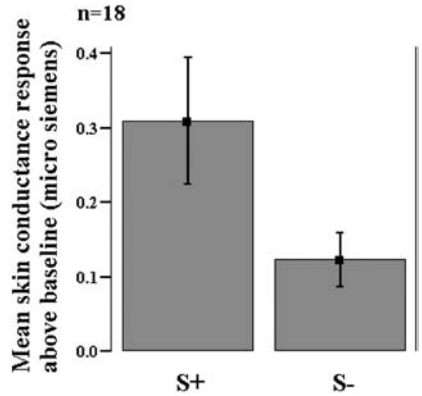


Fig. 4 The mean skin conductance response (μSiemens) to the S+ and S− (± SEM) collapsed across the final five S+ and S− trials of training in which the key-press response was not produced, in 18 participants who withheld at least one key-press response in both of these categories

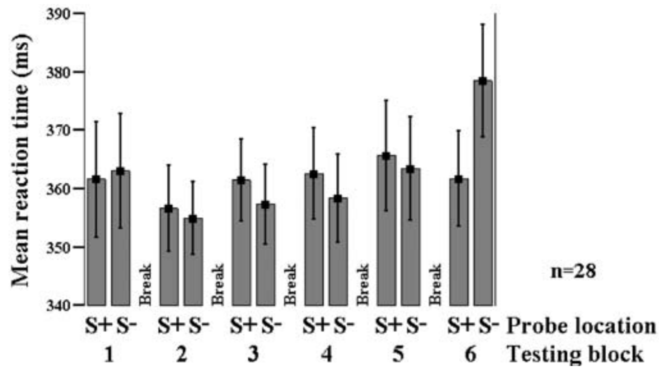


Fig. 5 Mean reaction times in ms (±SEM) for dot-probes in the same location as the S+ or S− in the six blocks of testing

Skin conductance

Analysis of the data shown in Fig. 4 revealed a significant main effect of stimulus [$F(1,17)=4.93$, $P<0.05$], indicating that the S+ had acquired the capacity to elicit a conditioned skin conductance response by the end of training.

Testing

Figure 5 shows the mean RT for dot-probes in the same position as the S+ and S−, over the six blocks of testing. ANOVA upon these data revealed a significant interaction between probe location and testing block [$F(5,135)=3.39$, $P<0.01$], and no reliable main effect of probe location ($F<1$) or testing block [$F(5,135)=1.31$, $P>0.05$]. The main effect of probe location was found to be reliable in testing block 6 [$F(1,27)=11.48$, $P<0.005$], and unreliable in testing blocks 1–5, largest [$F(1,27)=1.31$, $P>0.05$]. These data indicate that in testing block 6 participants responded more quickly to dot-probes in the same location as the S+ than the S−.

Correlations

Discrimination scores from training session 1 and 2, the skin conductance response to S+ and attentional bias scores from testing block 6 were correlated with the three questionnaire items that estimated participants' exposure to tobacco-smoke in the natural environment, cigarettes per day, years spent smoking and the FTQ scores, as well as subjective craving to smoke (QSU-brief scores obtained before training and testing). In addition, attentional bias scores were correlated with the skin conductance response to S+ and with discrimination scores from session 1 and 2.

The three questionnaire items that estimated participants' exposure to tobacco-smoke in the natural environment correlated significantly and positively with each other (Fig. 6) and significantly and negatively with discrimination scores from session 1 (Fig. 7).

Subjective craving to smoke obtained just prior to testing correlated significantly and positively with the attentional bias for the S+ in testing block 6 (Fig. 8A).

The attentional bias for the S+ in testing block 6 correlated significantly and positively with the skin conductance response to the S+ (Fig. 8B), and with the number of times the S+ was paired with tobacco-smoke in training session 2 (Fig. 8C), only if participants who produced a discrimination score greater than zero in training session 2 were included.

No other significant correlations were found.

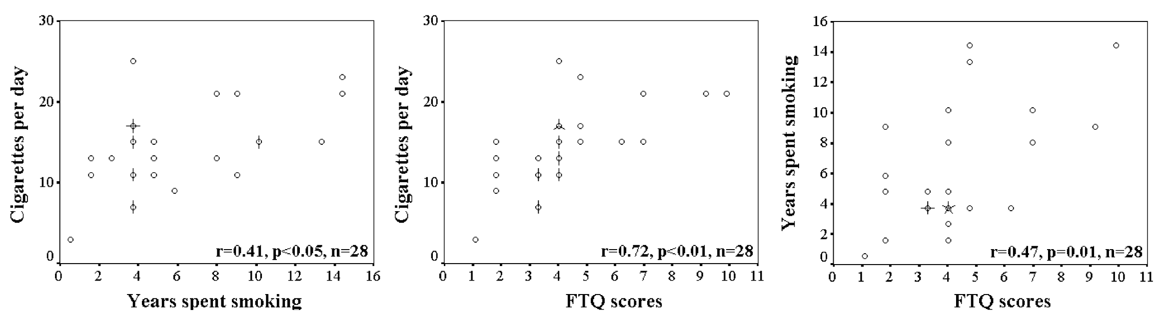


Fig. 6 Spearman's correlations and scatterplots of the relationships between the three questionnaire items, cigarettes smoked per day, years spent smoking and FTQ scores

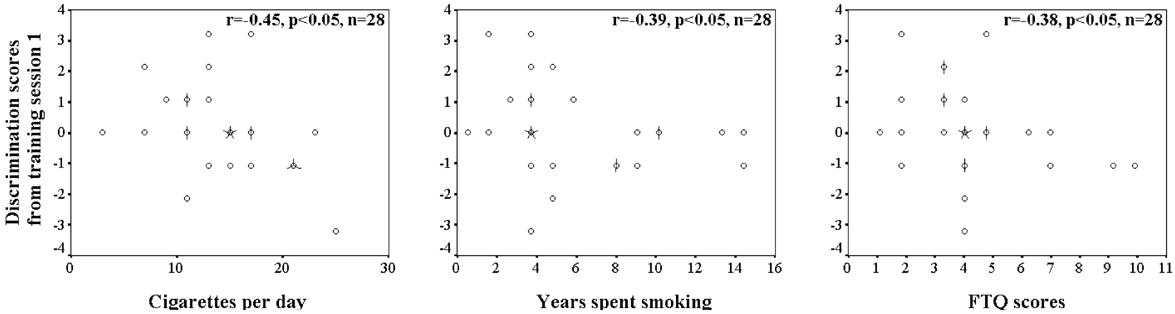


Fig. 7 Spearman's correlations and scatterplots of the relationships between discrimination scores from training session 1 and the three questionnaire items, cigarettes smoked per day, years spent smoking and FTQ scores

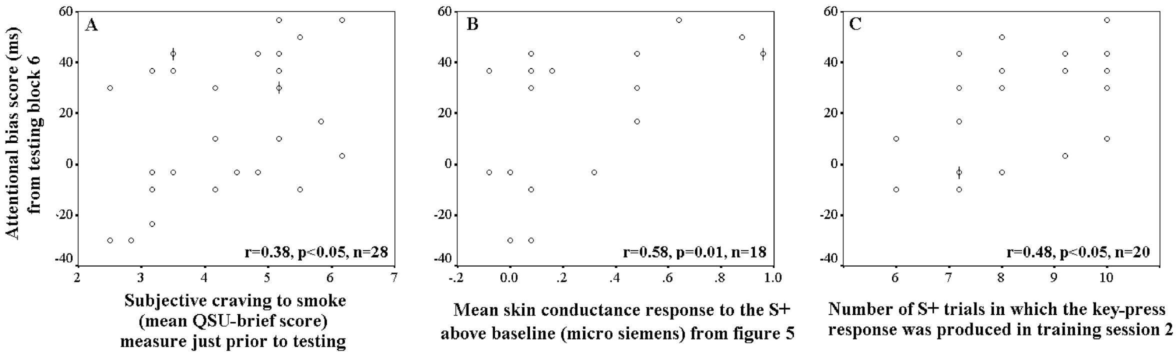


Fig. 8 Spearman's correlation and scatterplot for the relationship between attentional bias scores from testing block 6 and **A** subjective craving scores obtained with the QSU-brief just prior to testing, **B** the skin conductance response to the S+, and **C** the number of S+ trials in which the key-press response was produced in training session 2, from 20 participants who produced a discrimination score greater than zero in training session 2

Post hoc analysis: the light/heavy categorisation

We (Hogarth et al. 2003) recently found that light smokers (smokers of fewer than 20 cigarettes per day) expressed an attentional bias for smoking pictures in the dot-probe task, whereas heavy smokers (smokers of 20 or more cigarettes per day) did not. To determine if light and heavy smokers differed with respect to the attentional bias for the S+, smokers in the present study were categorised in the same way. Light and heavy smokers differed significantly with respect to all of the characteristics shown in Table 1 except for sex ratio, time since a cigarette and QSU-brief scores obtained just prior to testing.

The mean RTs of light and heavy smokers from testing block 6, shown in Fig. 9, were entered into ANOVA with the variable probe location (same as the S+, same as the S−). There was a significant main effect of probe location [$F(1,26)=11.95$, $P<0.005$] as before, and a reliable main effect of group [$F(1,26)=7.46$, $P<0.05$], but no significant interaction between group and probe location [$F(1,26)=1.66$, $P>0.05$]. These data suggest that although heavy smokers had slower RTs than light smokers, both groups allocated the focus of visual attention to the S+ in preference to the S−.

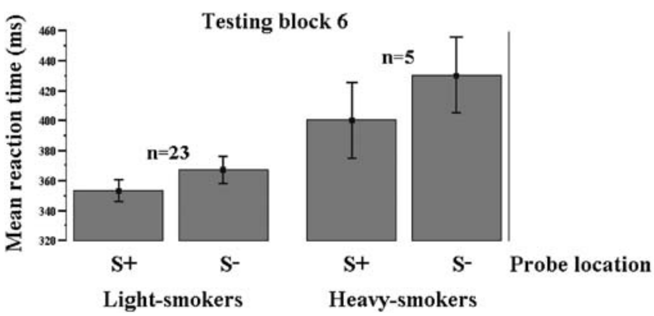


Fig. 9 Mean reaction times in ms (±SEM) for dot-probes in the same location as the S+ or S− in block 6 of testing from light smokers (smokers of less than 20 cigarettes per day) and heavy smokers (smokers of 20 or more cigarettes per day)

Discussion

In the discrimination phase of the study, smokers learned to perform the instrumental tobacco-seeking response selectively in the presence of the S+ relative to the S−, demonstrating that the S+ had acquired the capacity to elicit the instrumental tobacco-seeking response. This effect is consistent with previous findings that responding for tobacco-smoke and smoking behaviour are increased by smoking-related cues relative to control cues (Herman

1974; Glad and Adesso 1976; Suraway et al. 1985; Payne et al. 1990, 1991; Niaura et al. 1992; Perkins et al. 1994; Droungas et al. 1995; Mucha et al. 1998).

Rescorla and Solomon's (1967) classic two-process learning theory has described the learning mechanisms that subserve discriminative stimulus control of instrumental behaviour. According to Rescorla and Solomon's (1967) theory, the key-press response in the present study was acquired/maintained by the instrumental response-reinforcer contingency between key-press response and the tobacco-smoke outcome. By contrast, the capacity of the S+ to elicit the key-press response was acquired through the Pavlovian contingency between the S+ and the tobacco-smoke outcome. Consequently, discriminative stimulus control of instrumental behaviour is achieved through Pavlovian to instrumental transfer (Lovibond 1983; Hall et al. 2001; Borchgrave et al. 2002).

In the test phase of the study, smokers allocated the focus of visual attention to the S+ in preference to the S−, consistent with previous findings that smokers allocated the focus of visual attention to smoking-related cues in preference to neutral control cues in the dot-probe task (Ehrman et al. 2002; Mogg and Bradley 2002; Bradley et al. 2003; Hogarth et al. 2003). The capacity of the S+ to command attention presumably developed as a consequence of the Pavlovian contingency between the S+ and tobacco-smoke reinforcement that was inherent in the training procedure, as predicted by incentive salience theory (Sokolov 1963; Bindra 1978; Robinson and Berridge 1993). However, the command of attention by the S+ was only apparent in testing block 6. The delayed emergence of differential attention to the S+ and S− probably reflects the interaction between the effects of the retention interval and continued testing on generalization between S+ and S−. It is well established that generalisation gradients flatten across a retention interval between the end of discrimination training and the generalization test (e.g. Riccio et al. 1992). Consequently, it is likely that the 2-h retention interval enhanced the generalisation of attentional control from the S+ to the S− at the outset of the dot-probe testing. There is also evidence that generalization gradients sharpen with continued testing in extinction (Thomas and Barker 1964; Friedman and Guttman 1965). The dot-probe procedure presented the S+ without the tobacco-smoke reinforcer and therefore was effectively an extinction procedure. Consequently, it is not surprising that differential attention to S+ and S− only emerged at the end of testing.

The argument that the attentional bias for the S+ developed through Pavlovian conditioning is supported by the positive correlation between attentional bias scores from testing block 6 and the number of times the S+ was paired with tobacco-smoke reinforcement in training session 2. However, this correlation was only significant amongst participants who demonstrated that they had learned the discrimination in training session 2 by producing a discrimination score greater than zero. This finding is intriguing because all participants demonstrated awareness of the contingencies in the contingency awareness test at the end of training session 2. To explain these findings, it may be suggested that participants with larger discrimination scores became aware of the contingency between the S+ and tobacco-smoke at an earlier stage of training session 2 than participants with smaller discrimination scores, who became aware of the contingency towards the end of training. Consequently, participants with larger discrimination scores were cognisant of a greater number of pairings between the S+ and tobacco-smoke, which was critical for the S+ to acquire the capacity to command the focus of visual attention in testing (Carrillo et al. 2000).

The finding that the S+ elicited a larger skin conductance response than the S− at the end of training, demonstrated that discriminative instrumental contingencies did in fact bring about Pavlovian conditioning to the S+. Furthermore, if the skin conductance response to the S+ is interpreted as a Pavlovian conditioned response (Dawson and Schell 1982; Field and Duka 2002), the positive correlation between this response and the attentional bias for the S+ suggests the attentional bias for the S+ was also brought about through Pavlovian conditioning.

In our previous study (Hogarth et al. 2003), light smokers showed an attentional bias for smoking-related pictures versus control pictures in the dot-probe task, whereas heavy smokers showed no attentional bias, and the two groups were significantly different in this respect. In block 6 of the dot probe task in the present study, we found a significant main effect of probe location and an unreliable interaction between this factor and group (light smokers, heavy smokers). This null interaction does not appear to be due to low power (or the small number of heavy smokers) because post-hoc tests showed that the main effect of probe location was significant in both the light smoker group and the heavy smoker group, both $P<0.05$. Consequently, we conclude that light smokers and heavy smokers both showed an attentional bias for the S+ over the S−.

Why should heavy smokers show an attentional bias for the S+ in the present study, but not for the experimental smoking images in our previous study? One explanation for this difference may be derived from the principles of stimulus generalisation. Heavy smokers may have had greater exposure to the contingencies between ecological S+ and tobacco-smoke reinforcement than light smokers (Tiffany 1990; Baxter and Hinson 2001; see also Dickinson et al. 1995; Holland 1998), which has narrowed the generalisation gradient around their ecological S+ (Razran 1949) such that the capacity to command attention was not generalised to the novel experimental smoking pictures. By contrast, light smokers' reduced exposure to ecological contingencies may have resulted in a generalisation gradient that was sufficiently broad to encompass the experimental smoking pictures. In the present experiment, exposure to the experimental S+ contingency could not vary as much as exposure to the ecological contingencies, and so light smokers and heavy smokers produced attentional bias scores of similar magnitude. The implications of this argument are that both light smokers and heavy smokers express an attentional bias for smoke-paired S+ in the natural environment, but attentional responding in heavy smokers is more selective to the precise stimulus characteristics of their ecologically trained S+.

Although exposure to tobacco-smoke in the natural environment did not impact upon the attentional bias for the S+, such exposure appeared to influence discrimination learning. The three questionnaire items that were assumed to estimate participants' exposure to tobacco-smoke in the natural environment—cigarettes smoked per day, years spent smoking and FTQ scores—correlated positively with each other, supporting this assumption. Furthermore, the three questionnaire items correlated negatively with discrimination scores from training session 1, which may be interpreted as showing that as exposure to ecological contingencies between S+ and tobacco-smoke increases, the capacity to learn novel (in this case experimental) contingencies involving tobacco-smoke decreases.

Exposure to tobacco-smoke in the natural environment did not influence discrimination performance in training session 2, in contrast to training session 1. This finding may be interpreted as showing that the contingency awareness test administered after training session 1 evoked a more cognitive style of discrimination learning in training session 2, which was not disrupted by prior exposure to ecological contingencies between S+ and tobacco smoke.

Discriminative stimulus control of the tobacco-seeking response was more apparent in males than females in training session 2, suggesting that males learned the discrimination more quickly than females. This gender effect cannot be attributed to smoking history variables, because as shown in Table 1, males and females did not differ with respect to these variables. Other observations however, do provide a partial account of the gender effect. For example, no sex difference was found with respect to awareness of the stimulus-outcome contingencies at the end of training session 2, skin conductance or dot-probe task performance. However, females did perform the key-press response in more conditioning trials than males. These observations suggest that females learned the discrimination, but did not express this learning as selective performance of the key-press response in S+ trials because they pressed the key in greater conditioning trials overall, for a reason that is currently unknown.

Subjective craving to smoke correlated with attentional bias for the S+ in testing block 6, indicating that craving is associated with an increase in visual attentional selection of the tobacco-paired S+. However, craving did not correlate with the skin conductance response to the S+ or with any index of the vigour of the tobacco-seeking response. This latter null result is surprising because Carter and Tiffany (2001) obtained a positive correlation between craving and the speed of their tobacco-seeking response. There are two noteworthy procedural differences between these studies that could account for the differential findings. Firstly, Carter and Tiffany's (2001) tobacco-seeking response involved standing and reaching, whereas our response was a key-press, which might vary between-participants to a lesser extent. Secondly, Carter and Tiffany (2001) measured craving and the tobacco-seeking response on a trial-by-trial basis, whereas we measured craving before training. Our method provides fewer data points and reduces the temporal proximity of the craving and seeking measurements. We suspect that in the present design a correlation could be obtained between craving and tobacco-seeking behaviour if craving was measured just prior to each conditioning trial and if the latency to open the smoke box was recorded as the tobacco-seeking response.

In summary, previous studies have demonstrated that smoking-related cues command attention and elicit instrumental tobacco-seeking behaviour. To our knowledge, the present study is the first to demonstrate experimentally that the association between a neutral stimulus and smoking endows that stimulus with the capacity to command attention and to elicit instrumental tobacco-seeking behaviour. The implications of these findings are that stimuli associated with smoking in the natural environment acquire the capacity to command attention and elicit instrumental tobacco-seeking behaviour, and that this form of stimulus control of behaviour is at least partially responsible for tobacco addiction. It is easy to imagine that such stimulus control of behaviour could play a role in relapse to smoking (Shiffman 1986; O'Connell et al 1998), and the patterning of smoking topography (Isaac and Rand 1969, 1972).

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