Research report

Reward uncertainty enhances incentive salience attribution as sign-tracking

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HIGHLIGHTS

► Reward uncertainty is traditionally believed to reduce incentive motivation.
► However, uncertain rewards appear to make predictive cues more attractive.
► As can be seen in the form of increased sign-tracking to uncertain predictive cues.
► It also occurs if certainty about reward prediction is replaced by uncertainty.
► Thus, reward uncertainty is able to enhance the incentive motivational power of CSs.

ARTICLE INFO

ABSTRACT

Conditioned stimuli (CSs) come to act as motivational magnets following repeated association with unconditioned stimuli (UCSs) such as sucrose rewards. By traditional views, the more reliably predictive a Pavlovian CS–UCS association, the more the CS becomes attractive. However, in some cases, less predictability might equal more motivation. Here we examined the effect of introducing uncertainty in CS–UCS association on CS strength as an attractive motivation magnet. In the present study, Experiment 1 assessed the effects of Pavlovian predictability versus uncertainty about reward probability and/or reward magnitude on the acquisition and expression of sign-tracking (ST) and goal-tracking (GT) responses in an autoshaping procedure. Results suggested that uncertainty produced strongest incentive salience expressed as sign-tracking. Experiment 2 examined whether a within-individual temporal shift from certainty to uncertainty conditions could produce a stronger CS motivational magnet when uncertainty began, and found that sign-tracking still increased after the shift. Overall, our results support earlier reports that ST responses become more pronounced in the presence of uncertainty regarding CS–UCS associations, especially when uncertainty combines both probability and magnitude. These results suggest that Pavlovian uncertainty, although diluting predictability, is still able to enhance the incentive motivational power of particular CSs.

1. Introduction

Repeated Pavlovian association between a conditioned stimulus (CS) and an unconditioned stimulus (UCS) increases the predictive value of the CS relative to the UCS, a process that can be described in terms of correlation and computational models such as temporal difference or prediction error models [25,36,38,42,45,46,50]. Most formulations of reinforcement theory do not distinguish between the predictive and incentive values of a cue, so that a CS's incentive value is assumed to depend purely on its predictive value or associative strength, and to become more and more pronounced as the

CS–UCS pairings become more reliable [38,50]. The same general principle applies to the patch foraging theory in behavioral ecology – for which animals always tend to optimize the consequences of their actions, and hence exhibit a preference for situations associated with higher reward rates [31,54].

However, there is also evidence that prediction and incentive motivation are not identical [15,48,55,59]. Especially relevant to our current investigation of uncertainty are reports that individuals sometimes display a preference for uncertain rewards rather than for certainty – even when the uncertain option does not provide any advantage in terms of reward rate (e.g. [9,22,28,53]). This suggests that reward uncertainty may be a non-associative source of incentive motivation, just as are deprivation [39], drugs of abuse [47] that potentiate the reactivity of brain mesocorticolimbic systems. All these sources of stimulation share the ability to motivate behavior by means of mesolimbic dopamine, released in the nucleus accumbens from the ventral tegmental area [6]. In particular, there

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is a positive correlation between midbrain dopamine release and the uncertainty of reward delivery in monkeys [18] and humans [34,44]. Also, rats with lesions of the core region of the nucleus accumbens tend to prefer small certain rewards over larger uncertain rewards, while this preference is reversed in the absence of accumbens lesions [11].

Autoshaping is a Pavlovian procedure that is well adapted to assess the motivational magnet strength or attractiveness of a CS that predicts a UCS reward [14,19,21,37,57]. In this procedure, a lever is presented for a short period of time and its retraction is immediately followed by the delivery of a sucrose reward, irrespective of whether the animal engages the lever. Over training, two types of conditioned response develop. Some individuals preferentially display a sign-tracking (ST) response, which consists of appetitive approach and then vigorously nibbling, sniffing, and pressing the lever with consummatory actions that appear closely related to the ingestive sucrose reward. In contrast, other individuals produce a goal-tracking (GT) response, which consists of vigorously approaching the goal dish, and inspecting, nibbling and sniffing the inner location where the reward is delivered. The dopamine antagonist α-flupenthixol in the nucleus accumbens of rats may abolish ST without necessarily affecting GT, suggesting that the ST response especially requires mesolimbic dopamine to develop [19,21,57]. This suggests that ST is a plausible way of indexing incentive motivation.

Regarding uncertainty in autoshaping, Boakes first described in 1977 the surprising finding in rats that a relatively uncertain 50% contingency of partial reinforcement in CS–UCS relationship actually produced higher rates of sign-tracking expressed as CS lever-pressing (and lower goal-tracking) than a fully predictive 100% contingency [9]. Similar reports of finding stronger autoshaping under Pavlovian partial reinforcement than under full 100% reinforcement subsequently appeared also for pigeons (e.g. [12,26]). In the present study, we investigated the effects of uncertainty in rats further, by examining two different types of CS–UCS uncertainty: reward UCS magnitude (e.g., large versus small) and reward probability (e.g. full 100% versus partial or unpredictably varying reinforcement outcome), alone and in combination, on the acquisition and expression of ST and GT responses in an autoshaping procedure (Experiment 1). We also examined the motivational magnet features of the predictive lever CS+ more closely by conducting a detailed videoanalysis of appetitive-consummatory sequences in sign-tracking, consisting of behavioral approach followed by intense ingestive-type nibbles and sniffs directed specifically toward the metal CS+. We also tested the temporal effects of within-individual shifts in certainty to uncertainty (Experiment 2). This study aimed to determine (i) the extent to which different behavioral indicators of ST and GT are affected by the unreliability of the CS in several conditions of reward uncertainty, and (ii) how the sudden occurrence of reward uncertainty after repeated exposure to reward certainty modifies the expression of ST and GT responses.

2. Experiment 1

2.1. Materials and methods

2.1.1. Animals and housing conditions

Female Sprague-Dawley rats ($N = 56$, age: 12–14 weeks old, weight: 150–325 g) were individually housed with ad libitum access to tap water. Rats were handled and partly deprived of food until reaching approximately 85% of free-feeding body-weight. They were maintained in this deprivation state throughout the experimental procedure. The last two days before the beginning of the training sessions, rats were familiarized with 45-mg sucrose pellets in their home cage. Rats were kept under a reverse 12:12 h light-dark cycle (lights on at 9 p.m.) and constant temperature (21 °C). All experimental procedures were approved by the University Committee on the Use and Care of Animals at the University of Michigan.

2.1.2. Autoshaping chambers

Autoshaping chambers (30 cm × 24 cm × 21 cm) contained two levers (4.5 cm × 2 cm) and a recessed pellet magazine dish (3 cm × 2 cm × 1 cm). The levers were arranged with one on each side of the magazine, which was located in the center of a lateral wall near the floor of the chamber. Each lever had a light at the base that was turned on with its presentation, and an auditory tone (2.9 kHz) was programmed to be produced during lever presentation. An infrared beam and sensor recorded a magazine entry each time the beam was broken. The number of lever presses and magazine entries were recorded using MedPC® software and Med Associates® hardware. The floor, ceiling, and sides of the chambers were made of Plexiglas to allow for video recording. A first camera positioned below the chamber pointed directly upward and a second camera positioned behind the chamber pointed toward the magazine and the two levers. Chambers were placed in cabinets to ensure reduced ambient light and noise. Red LED house lights were mounted to the ceiling and floor of the cabinet and were turned on during the training sessions.

2.1.3. Groups

Rats were divided into four groups ($N = 14$ per group) according to the type of CS–UCS pairings to which they were exposed. Each group was characterized in terms of a probability (100% or 50%) and a magnitude (0, 1, 2 or 3 pellets) of reward delivery per trial.

- 100%-1 (no uncertainty [100% certainty]): rats received one sucrose pellet for each presentation of the lever, that is, a total of 40 pellets per session.
- 50%-2 (probability-based uncertainty): rats received either 2 or 0 pellets with a 50% probability for each lever presentation, that is, on average 40 pellets per session.
- 100%-1–2–3 (magnitude-based uncertainty): rats received 1, 2 or 3 pellets on a random basis (33.3% for each reward amount) for each lever presentation. Here, the animals were exposed to 78–82 pellets per session.
- 50%-1–2–3 (combined probability/magnitude uncertainty): on average, rats received either no pellet with a 50% probability, or 1, 2 or 3 pellets with an equal probability (16.7% for each reward amount) for each lever presentation. The rats obtained a total of 38–42 pellets per session.

2.1.4. Procedure

The day after magazine training – one session of 20 sucrose pellets delivered in the absence of lever presentation – rats started the training sessions under a specific condition of CS–UCS pairings, as mentioned above. Training consisted of one daily session of 40 trials for five consecutive days. Each trial consisted of a presentation of an illuminated lever – located on the right side of the magazine – that became available for 8 s on a variable inter-trial interval (range: 30–90 s) and was accompanied by an auditory tone. The function of the light was the same as that of the tone, forming a compound CS that predicted impending sucrose reward (illuminated lever with tone). The illuminated lever insertion provides a discrete localized and salient object that can become the target of conditioned motivation. The tone further adds to perceptual salience and alerts the rat even when not looking toward the lever location (and causing the rat to immediately orient to the lever). Depending on the experimental condition and/or trial, zero to three sucrose pellets were delivered in the magazine immediately after retraction of the lever. A control lever was constantly available on the left side of the magazine over the sessions. During the sessions, the rats had free access to a tap water dispenser located at the back of the chamber. The number of lever presses and magazine entries was automatically recorded for each session, and the last training session was video recorded for complementary analyses. Rats were returned to their home cage at the end of each session.

2.1.5. Behavioral video scoring

In addition to the automatically recorded number of lever presses and magazine entries, the following behaviors mentioned below were manually counted on the basis of video recordings on training day 5.

- *Look*: head movement toward the lever or magazine without approaching it.
- *Approach*: body (other than head) movement toward the lever or magazine (does not require contact with either the lever or magazine).
- *Lever/Magazine contact*: the lever or magazine was approached to within a distance < 1 cm.
- *Sniff*: small amplitude, short duration exploratory movement of the lever or magazine with the nose, making little or limited contact.
- *Nibble*: small amplitude, short duration exploratory movement of the lever or magazine with the mouth, making contact.
- *Slow bite* (lever *only*): orally grasping the lever between their mandibles.
- *Slow dive* (magazine *only*): insertion of the nose and mouth into the food cup, as would normally occur when retrieving a sucrose pellet.
- *Time latency before lever/magazine contact*: time elapsed before reaching the lever or magazine once the lever became available.

• *Mean distance from lever/magazine*: approximate distance of the rat's nose from the lever or magazine within an 8-s interval. Distance was assessed three times within the interval (i.e. 0–4–8 s).

2.1.6. Statistical analyses

We focused on the expression of sign-tracking behavior specifically in sign-trackers. An individual was considered as a sign-tracker provided that the number of lever presses was at least 75% greater than the number of magazine entries. Mixed individuals were excluded from analyses, even though they sometimes pressed the lever a larger number of times – this occurred only twice in the 100%-1 group and, in both cases, the number of lever presses remained below the 75% criterion. On this basis, the eight individuals (out of 14) with the highest percentage of lever presses to magazine entries were selected in each group according to their performance on session 5 (see [20]).

This selection method was justified by the fact that the number of goal-trackers and of mixed individuals was heterogeneously spread among the different groups (e.g. 4 goal-trackers in the 100%-1–2–3 vs. 1 goal-tracker in the 50%-1–2–3), so that they induced potentially problematic imbalances with respect to their impact on average ST performance in each group. Selecting the best sign-trackers within the four groups was an objective way of suppressing those imbalances and, thus, of comparing the most CS-motivated individuals.

A two-way ANOVA was computed to determine the Group × Day effects with respect to the number of lever presses and magazine entries. For each rat, every five trials – i.e. 1–5–10–15–20–25–30–35–40 – of session 5 were analyzed by video scoring. One-way ANOVAs were used in order to assess the effects of group on the behavioral parameters extracted from videos. Lever- and magazine-directed behaviors were considered both during the 8-s period prior to lever presentation and during the 8-s period of lever presentation. Repeated measures ANOVAs between days 1–5 allowed us to examine the ability of rats to learn the task within each group. All comparisons between two data sets were computed using planned comparisons. The null hypotheses were rejected at $p < 0.05$.

2.2. Results

Across training sessions in general, the number of lever presses ($F_{(4,140)} = 21.979$, $p = 0.000$) and magazine entries ($F_{(4,140)} = 11.349$, $p = 0.000$) significantly increased, but no effect of group ($F_{(3,140)}$'s < 1.9, ns) or Group × Day interaction ($F_{(12,140)}$'s < 1, ns) was apparent in simple number of presses. The increase in lever presses, as well as the decrease in magazine entries, was shown within each group between days 1–5 (repeated measures for lever presses: $F_{(2,6)}$'s > 17, $p < 0.004$; magazine entries: $F_{(2,6)}$'s > 8, $p < 0.02$). Thus, the task was correctly learned, irrespective of the testing conditions. However, an effect of group occurred when a ratio between the number of lever presses and the number of magazine entries was computed ($F_{(3,140)} = 4.393$, $p = 0.005$). As shown in Fig. 1, this ratio was significantly higher on the last day of training (day 5) in the 50%-1–2–3 group than in the 100%-1 group ($F_{(1,28)} = 9.119$, $p = 0.005$) and the 100%-1–2–3 group ($F_{(1,28)} = 6.877$, $p = 0.014$). It must be noted that the presses/entries ratio means tended to increase with the uncertainty of reward delivery – although no other significant differences were observed ($F_{(1,28)}$'s < 3.5, ns). Importantly, the main results are maintained when the six originally-excluded rats were added to the eight sign-tracking individuals first taken into account for analyses, showing a strong bias in lever pressing in the 50%-1–2–3 rats as compared to those exposed to 100%-1 ($F_{(1,52)} = 5.739$, $p = 0.02$) or 100%-1–2–3 ($F_{(1,52)} = 9.813$, $p = 0.003$).

We observed relatively few goal-trackers and mixed GT/ST individuals showing both responses in this experiment. Only one or two goal-trackers or GT/ST individuals were observed in most groups, even in the 100%-1 certainty condition. While fewer goal-trackers or GT/ST individuals might be expected in uncertainty groups if uncertainty strengthens the propensity to sign-track, the low incidence in the 100% predictable group makes it difficult to draw any strong inferences. The only group that had a substantial proportion >30% goal-trackers was the 100%-1–2–3 group that on average received twice the number of sucrose pellets than other groups, but again it is impossible to be certain whether UCS magnitude influenced goal-tracking or whether this was a random variation in ST versus GT individuals.
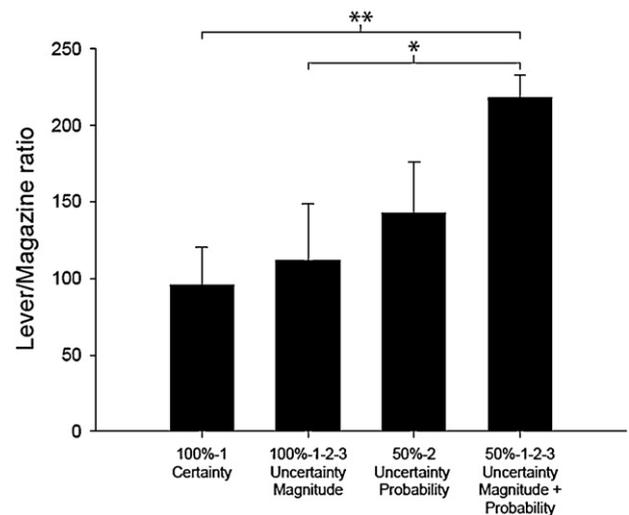

Fig. 1. Lever presses to magazine entries ratios on training day 5 for Experiment 1. Four groups of animals are trained for 5 days under varying levels of reward certainty. Either 100%-1, where each CS presentation is followed by a single pellet delivery; 100%-1–2–3, where each CS is followed by either 1, 2 or 3 pellets with equal probability; 50%-2, where only half of all CS presentations are rewarded, but where each rewarded trial consists of 2 pellets; 50%-1–2–3, where half the trials were rewarded by either 1, 2 or 3 pellets with equal probability. On average, ratios tended to increase as the ability to predict the magnitude and probability of future reward decreased, *$p < 0.05$; **$p < 0.01$.

It is hard to explain why this experiment did not replicate the basic 50% ST effect reported in older studies [9]. In principle, the presence of a water dispenser here might have induced polydipsia as a response to compete with sign-tracking – i.e. intense drinking behavior in animals subjected to intermittent delivery of food [16,52]. However, no substantial amounts of drinking were observed here, suggesting schedule-induced polydipsia was not the explanation. In fact, three out of the eight rats did not drink at all, while the two rats that drank the most were also among the best performers in lever pressing within the 50%-2 group – i.e. 215 and 209 responses, respectively. Overall, there was no correlation between the time spent drinking and the number of lever presses among the eight individuals (Pearson's $r = 0.26$, ns).

On day 5, video analysis of the 8-s baseline period prior to the CS lever presentation revealed no difference in lever-directed ($F_{(3,28)}$'s < 1, ns) or magazine-directed ($F_{(3,28)}$'s < 1.9, ns) behavior. However, as shown in Fig. 2, upon presentation of the CS lever, the 50%-1–2–3 group showed a significantly shorter latency to reach the lever than the 100%-1 group ($F_{(1,28)} = 9.256$, $p = 0.005$), and this occurred despite the initial distance from the cue when it came out being only slightly different (50%-1–2–3: 9.097 ± 1.32; 100%-1: 11.722 ± 0.93 cm) – distance of the rats' nose from the center of the retracted lever was assessed just before the lever emerged from the wall every five trials. Finally, the number of lever-directed bites was higher in the 50%-2 group than in the 100%-1–2–3 group ($F_{(1,28)} = 8.56$, $p = 0.007$). No significant difference was shown for magazine-directed behaviors during presentation of the lever ($F_{(3,28)}$'s < 1.07, ns).

2.3. Discussion

In autoshaping, rats that increase lever pressing (i.e. sign-tracking) over training sessions also tend to decrease the number of head entries in the magazine (i.e. goal-tracking) – a trade-off phenomenon that has been hypothesized to result from a competition between both behaviors [9]. Interestingly, the degree of
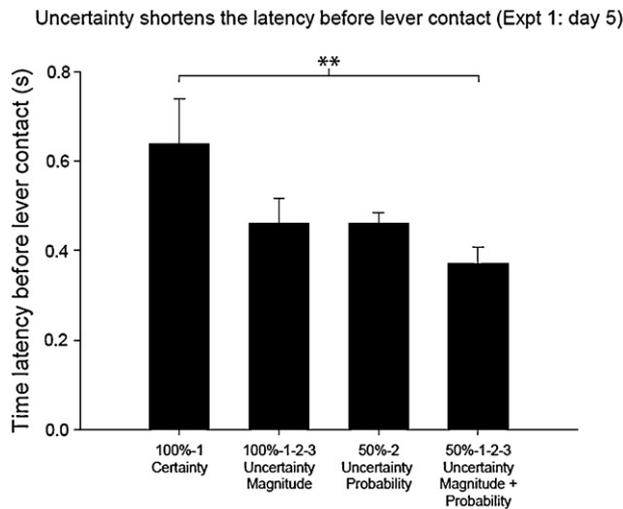
Uncertainty shortens the latency before lever contact (Expt 1: day 5)

Fig. 2. Time latency before lever contact measured on day 5 for Experiment 1. Latency tended to decrease as the ability to predict future reward decreased. It measures the time that each animal under four different conditions of certainty took to approach and contact the CS lever upon its presentation, **$p < 0.01$.

this trade-off between lever presses and magazine entries here was shown to be more pronounced under combined uncertainty (probability and magnitude) conditions than under the 100% prediction condition. Shorter time latency before reaching the lever and a larger number of lever-directed bites were also observed when the uncertainty involved combination of reward probability/magnitude or reward/no-reward probability – i.e. in the 50%-1–2–3 and in the 50%-2 group, respectively. These data suggest that rats subjected to reward probability uncertainty are more attracted to engage the lever. It may be of interest to note that the 100%-1–2–3 group (pure reward magnitude uncertainty) did not differ from the 100%-1 group (full prediction). Consistently, Kacelnik and Bateson [31] have shown in a review that animals generally prefer a certain option rather than an uncertain option when the amount (magnitude) of food outcomes is unpredictably variable. Thus, magnitude uncertainty regarding food outcomes does not seem particularly attractive. In contrast, combining magnitude uncertainty with probability uncertainty markedly magnified the lever attraction in the 50%-1–2–3 group. Our results suggest that an uncertain outcome may increase the intensity of Pavlovian appetitive motivation toward its CS. This possibility was explored further in Experiment 2.

3. Experiment 2

3.1. Materials and methods

3.1.1. Animals and housing conditions

Twenty-three female Sprague-Dawley rats (age: 12–14 weeks old, weight: 220–290 g) were subjected to the same housing and deprivation conditions as the rats used in Experiment 1. They were also trained using the same autoshaping chambers.

3.1.2. Procedure

3.1.2.1. Phase 1: reward certainty training. After magazine training, rats ($N = 23$) received daily sessions of 25 trials in the absence of reward uncertainty (100%-1: one food pellet for each lever presentation) for three consecutive days. The active lever was located on the left side of the magazine and the 8-s lever presentations were associated with a white noise generator. The lever on the right side was maintained retracted during this 3-day phase.

3.1.2.2. Phase 2: reward uncertainty training. Following day 3, rats were randomly divided into two groups. One group ($N = 12$) was subjected to 5 daily sessions of 25 trials in the combined reward uncertainty condition (i.e. 50%-1–2–3), while the other group ($N = 11$) continued being exposed to the condition previously experienced (i.e. 100%-1) for five consecutive days. (For details, see Experiment 1.) In order to increase

the chance that the rats of both groups were able to dissociate this second testing phase from the first one, phase 2 was conducted on a new lever associated with a 2.9-kHz tone rather than white noise. This new lever was located on the right side of the magazine, while the previous lever was now retracted and no longer available. A control lever was constantly available at the back of each chamber during the sessions. All other details of the procedure were identical to those described in Experiment 1. Behavior was video recorded for the last session of each phase (i.e. days 3 and 8).

3.1.3. Statistical analyses

The eight sign-trackers of each group were selected by means of the same method as that used in Experiment 1 – except that their performance was considered on day 8 (i.e. the last day of phase 2) instead of day 5. We analyzed the performance of rats for the last day of phase 1 (day 3) and phase 2 (day 8). In addition, MATLAB was used to compare the mean vector length created by the change in lever presses and magazine entries between day 3 and day 8 for either group. The data was then shuffled and 8 vectors were randomly picked from the combined set of vectors from both groups and drawn 100,000 times to calculate a distribution that was then compared to the mean resultant vector length for either group. Behavioral analysis was otherwise identical to Experiment 1.

3.2. Results

3.2.1. First phase: days 1–3

On day 3, there were no significant differences between the animals of both groups for any behavioral variable ($F_{(1,28)}$'s < 2.66, ns), nor during the subsequent 8-s CS lever presentation ($F_{(1,28)}$'s < 1.65, ns). This suggests that the rats of both groups reacted similarly to the lever and to the magazine under 100% certainty conditions.

In both groups, during the pre-CS lever interval, the magazine received a larger number of visits than the location close to the lever – which was retracted at that time. In particular, the magazine was significantly more approached (50%-1–2–3: $F_{(1,28)} = 9.216$, $p = 0.005$; 100%-1: $F_{(1,28)} = 4.592$, $p = 0.041$) and more nibbled (50%-1–2–3: $F_{(1,28)} = 5.56$, $p = 0.02$; 100%-1: $F_{(1,28)} = 6.344$, $p = 0.018$) than the lever. During CS lever presentation on day 3, the 50%-1–2–3 group displayed more magazine entries than lever presses ($F_{(1,112)} = 5.702$, $p = 0.019$), while no significant difference was shown in the 100%-1 group ($F_{(1,112)} = 0.325$, $p = 0.57$). At this stage, given the large number of goal-tracking responses, the magazine seemed to be at least as attractive as the lever.

3.2.2. Second phase: days 4–8

By day 8, in the group that remained on constant 100% certainty, 63% (7/11) were sign-trackers, 27% (3/11) were mixed GT/ST and 9% (1/11) was a goal-tracker. By comparison, in the group shifted to combined uncertainty, nearly all rats were sign-trackers: 92% (13/14) and 8% (1/14) was a goal-tracker. In terms of response intensities, we will focus here on the eight best performers in lever pressing from each group – one of them was a mixed GT/ST individual in the 100% condition, but its performance in lever presses (69) fell in the group's variability range (21–142). On day 8 after 5 days of the altered schedule, the 50%-1–2–3 group showed a reduced GT-related interest in the magazine during the pre-CS interval (prior to CS presentation), approaching and sniffing it less than the 100%-1 group (approach: $F_{(1,28)} = 4.379$, $p = 0.045$; sniff: $F_{(1,28)} = 4.426$, $p = 0.044$). These differences were absent on earlier day 3 (approach: $F_{(1,28)} = 0.287$, $p = 0.596$; sniff: $F_{(1,28)} = 2.658$, $p = 0.114$). No significant differences between the two groups were noted with respect to lever-directed approaches and sniffs prior to the presentation of the CS (approach: $F_{(1,28)} = 2.05$, $p = 0.163$; sniff: $F_{(1,28)} = 2.192$, $p = 0.15$). In addition, the 100%-1 group showed a far greater interest for the magazine than the retracted lever by preferably approaching it during the pre-CS interval ($F_{(1,28)} = 4.853$, $p = 0.036$), whereas this was not the case in the 50%-1–2–3 group, who approached both cues equally ($F_{(1,28)} = 2.378$, $p = 0.134$). These results during the pre-CS intervals indicate that the rats of both groups tend to differ in several respects relative to their interactions with the retracted lever and the magazine, despite the absence of
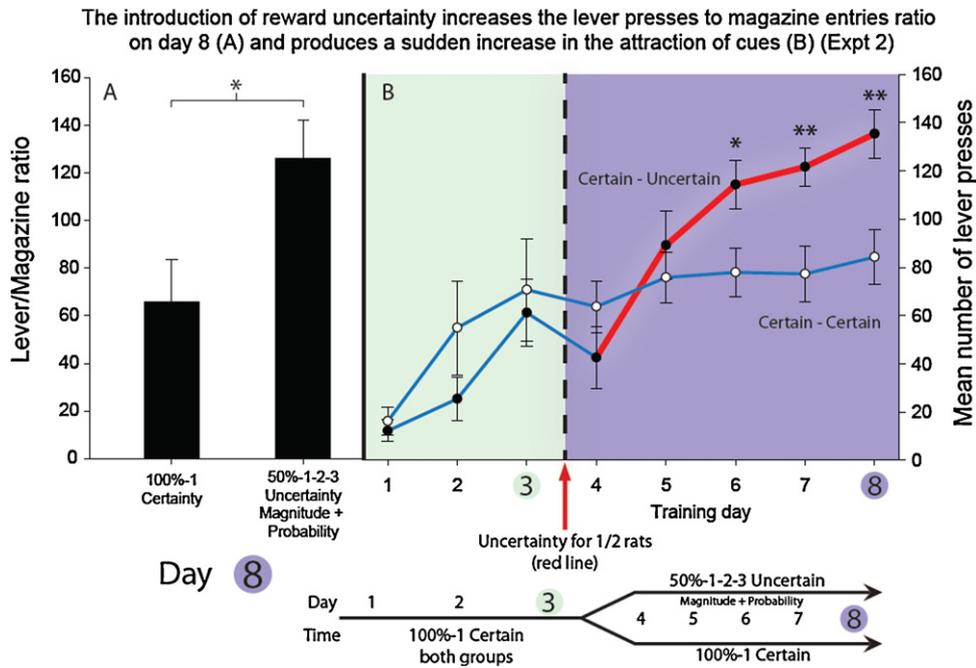
Fig. 3. Lever presses to magazine entries ratios on training day 8 and performance in lever presses over the eight training sessions for Experiment 2. As depicted in the line diagram at the bottom of the figure, all animals are initially trained under certain conditions (100%-1) for the first 3 days, at which point half the rats are switched to uncertain conditions (50%-1–2–3), while the other half remain under a certain protocol. (A) On the final day of training (day 8), animals exposed to reward uncertainty (50%-1–2–3) for the last five days focused their attention and efforts more greatly on the predictive CS lever than on the magazine, in comparison to animals constantly exposed to reward certainty (100%-1). (B) Sudden exposure to reward uncertainty induced a significantly larger number of lever presses after only a three-day period in the 50%-1–2–3 rats, $*p < 0.05$; $**p < 0.01$.

any CS. The magazine seemed to be attractive (per se and in comparison with the lever) in the 100%-1 rats, while no or little preference was shown in the 50%-1–2–3 rats.

Subsequent presentation of the CS lever for 8 seconds, gave rise to a Group × Day interaction ($F_{(7,112)} = 3.229$, $p = 0.004$) for lever presses and a significant effect of day ($F_{(7,112)} = 14.689$, $p = 0.000$), but no simple effect of group ($F_{(1,112)} = 2.781$, $p = 0.098$). Relevant to the Group × Day interaction, during presentation of the CS lever on day 8, the rats that were exposed to reward uncertainty (50%-1–2–3) performed a significantly larger number of ST lever presses than the rats in the 100%-1 group ($F_{(1,28)} = 6.02$, $p = 0.021$), despite not differing in this respect on day 3 ($F_{(1,28)} = 0.208$, $p = 0.652$) (Fig. 3B). As in Experiment 1, the lever presses to magazine entries ratios differed significantly between the two groups on day 8 ($F_{(1,14)} = 6.403$, $p = 0.024$) (Fig. 3A). Both groups did however display a significant increase in lever presses between days 3–8 (repeated measures for 50%-1–2–3: $F_{(2,6)} = 93.869$, $p = 0.000$; 100%-1: $F_{(2,6)} = 30.878$, $p = 0.001$). In contrast, 5 days of exposure to the uncertainty condition in the 50%-1–2–3 group led to a significant reduction in GT magazine entries between days 3 and 8 (repeated measures: $F_{(2,6)} = 23.439$, $p = 0.001$). This was not the case regarding the 100%-1 group that remained under certain conditions throughout (repeated measures: $F_{(2,6)} = 4.198$, $p = 0.072$). In other words, the number of magazine entries was similar in both groups on day 8 ($F_{(1,28)} = 0.40$, $p = 0.532$), despite being slightly more frequent in the 50%-1–2–3 group on day 3 ($F_{(1,28)} = 4.273$, $p = 0.048$). These automated responses provide a clear indication that reward uncertainty produced a shift in attractiveness in favor of the CS lever and away from the magazine during the CS presentation. This general tendency also occurred when the excluded rats were included in the analysis. However, although the mean number of lever presses was more elevated in the rats subjected to uncertainty on day 8 (103.25 ± 16.26 vs. 66.09 ± 12.51), no significant difference between the two groups was shown ($F_{(1,21)} = 3.192$, $p = 0.088$).
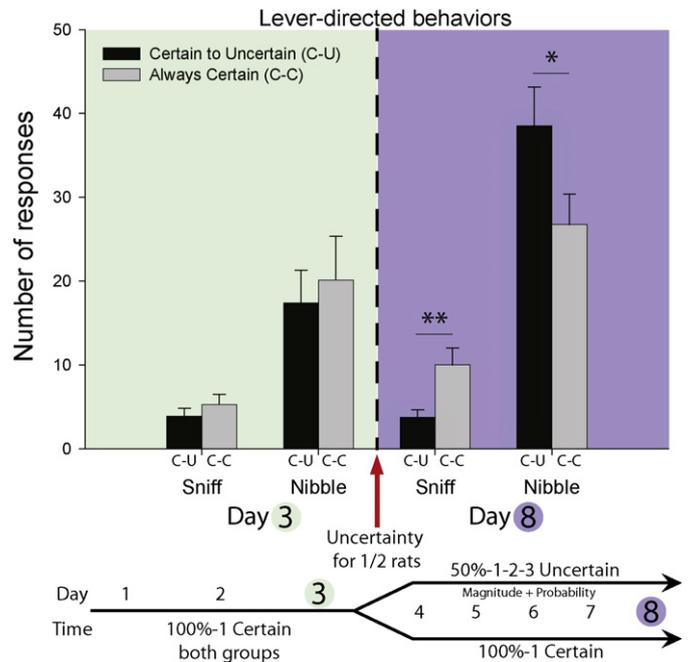

Fig. 4. Sniffs and nibbles directed at the lever during CS presentation for Experiment 2. After 3 days of training (under certain conditions), both groups showed similar performances on day 3. However on day 8, after either 5 days of certain or uncertain conditions, the rats subjected to reward uncertainty sniffed less and nibbled more at the lever than the rats maintained under constant reward certainty, $*p < 0.05$; $**p < 0.001$.

As illustrated by Fig. 4, after uncertainty shift, the number of ST lever-directed nibbles was also significantly larger in the shifted 50%-1–2–3 group compared with the constant 100%-1 group ($F_{(1,28)} = 7.122$, $p = 0.012$). This rise in ingestive-type nibbles was the largest single effect of uncertainty on consummatory behaviors. However, the number of lever sniffs was significantly larger in the 100%-1 group as opposed to the 50%-1–2–3 group ($F_{(1,28)} = 15.337$, $p = 0.000$). Nibbles might be construed as a slightly more intense consummatory action than sniffs, in the sense that nibbles involve ingestive-type movements requiring actual tooth and inner mouth contact with the metal lever, which sniffs do not. This nibble enhancement therefore may be in keeping with our conclusion that uncertainty promotes attraction. But then how to explain the smaller reduction in sniffs? A possible answer might arise based on the strong enhancement of nibbles by uncertainty, and the limited 8 s period of lever presentation to emit either nibbles or sniffs toward the object. We suggest there might possibly be a degree of response competition between the two responses, so that one excludes the other. In particular, competition and mutual subtraction might apply when response levels are maximal for the given 8-s period, such as is the case regarding the very high level of nibble responses under uncertainty, especially considering that response levels were similar in the two groups on day 3 ($F_{(1,28)} = 0.153$, $p = 0.699$). Such a result is difficult to interpret. But it could be argued that the limited time the rats had at their disposal to engage the lever (8 s) did not allow them to exhibit more sniffs, more nibbles and more bites in one group as opposed to the other. All rats tended to exploit the lever – because they were the best sign-trackers in each group – while having to give priority to one behavior over another. The fact that the rats decided to nibble rather than sniff the lever under uncertainty might be an indication that they engaged the lever with greater interest, and may explain the more frenzied appearance that the video tended to reveal (see [14]). In line with this view, we noted that the number of lever-directed bites was, on average, slightly more elevated in the 50%-1–2–3 group (13.5 ± 3.128) than in the 100%-1 group (9.125 ± 1.968).

Regarding the magazine, it is worth noting that rats in the 50%-1–2–3 group reduced their interest in the magazine and came less frequently in contact with it on day 8 ($F_{(1,28)} = 4.69$, $p = 0.039$), despite being similar to the 100%-1 group on day 3 ($F_{(1,28)} = 1.412$, $p = 0.245$). In contrast, animals in the 100%-1 group stayed closer to the magazine over the 8-s interval on day 8 ($F_{(1,28)} = 4.423$, $p = 0.044$), which was not initially the case on day 3 ($F_{(1,28)} = 0.008$, $p = 0.929$). Finally, the occurrence of reward uncertainty (Fig. 5A) tended to generate stronger sign-trackers than constant reward certainty (Fig. 5B), despite the sign-tracking propensity of rats exposed to constant certainty being more pronounced on day 3. We plotted the response of each animal on day 3 and compared it to day 8, using for each day the number of lever presses and magazine entries that the animal performed as coordinates. Using those same coordinates we established a vector corresponding to the change in behavior for each animal between day 3 and day 8. Therefore each vector length represents the amount of behavioral change between day 3 (where the tendency to goal-track was higher than that to sign-track) and day 8 (where the reverse tendency was observed). We then compared the mean vector length between these two days for each group (MATLAB), showing that the introduction of uncertainty created a significantly larger shift (mean resultant vector length) toward higher sign-tracking than constant certainty ($p = 0.015$).

3.3. Discussion

The results of this second experiment bring additional support to the hypothesis that reward uncertainty increases ST and the attribution of incentive salience to a discrete CS lever cue.

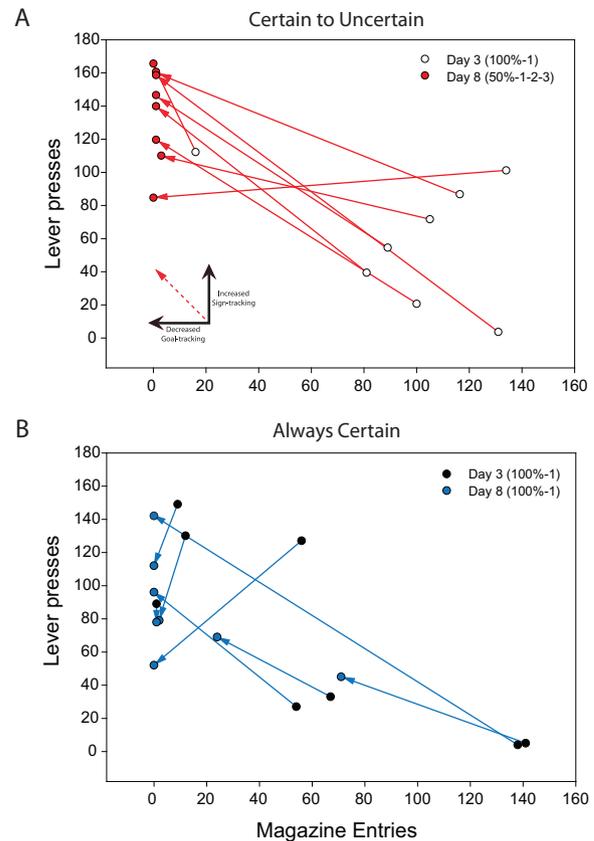Uncertainty increases incentive salience attribution to a CS lever

Fig. 5. Representation of the change in the ratio between the number of lever presses and the number of magazine entries for the eight rats of each group on day 3 and day 8 (Experiment 2). The two panels depict the impact of the last 5 days of training on each individual animal's responding between day 3 (both groups under certain conditions) and day 8 (one group exposed to uncertainty). The total number of lever press responses and magazine entries during CS presentations for each individual on training day 3 and again at day 8 are used as coordinates and connected for each individual to create a vector for their change in behavior. The amount of behavioral change is represented by vector direction and length. (A) Sudden exposure after day 3 to uncertain conditions led to more consistent behavioral change in the form of increased sign-tracking and decreased goal-tracking by day 8, as represented by significantly more coherent vector direction and length, in contrast to (B) individuals exposed to constant reward certainty.

Importantly, and unlike Experiment 1, increased ST under reward uncertainty here was obtained *within* a group of rats that originally was trained under certainty and who were initially indistinguishable from another group of rats never exposed to uncertainty. When uncertainty was subsequently imposed, we recorded a shift in interest and in the amount of incentive salience attributed to the predictive cue, as evidenced by more lever presses and less magazine contacts.

4. General discussion

The present study indicates that reward uncertainty associated with a CS may generate greater incentive motivation (or 'wanting') toward that reward cue, and that it may also do so even when initially presented with a cue reliably predicting reward. This tends to confirm earlier results reported by Boakes and others [9,12,13,26]. Our study also suggests that the enhanced motivational power of a CS that predicts uncertain reward only occurs under some conditions. First, ST – as a way of indexing the motivational effects of the CS – is more pronounced for uncertainty about probability (the animal does not know whether the next trial will be rewarded) than for

uncertainty about magnitude (the animal knows that the next trial will be rewarded, but ignores how much will be received). Indeed, no significant differences were found between the 100%-1–2–3 and the 100%-1 or between the 50%-2 and the 50%-1–2–3 groups, suggesting that the two 100%-reward groups are similar to each other, just as the two 50%-reward groups are in many respects as well, while differences were found between the 50%-1–2–3 group and the 100%-1 group, and also between the 50%-2 and 100%-1–2–3. More importantly, combining the two types of reward uncertainty (probability and magnitude) magnified ST as expressed by appetitive and consummatory behaviors toward the lever CS. This is apparent when the ratios between the number of lever presses and magazine entries are compared, and is also evidenced by a more rapid approach of the CS cue when it is presented, and more vigorous nibbles during the 8 s it remains available.

Reward uncertainty has given rise to a vast literature, from behavioral ecology to behavioral neuroscience and neuroeconomics (e.g. [1,9,10,13,17,22,24,27,28,31,40]). An important issue remaining is to explain *how* reward uncertainty can become a source of motivation. Boakes [9] originally suggested that ST and GT responses compete for the control of behavior, and that partial reinforcement would reduce the strength of GT, resulting in stronger ST. Such a disinhibition process could indeed explain why ST increases under a 50% probability compared with a 100% probability. However, it makes difficult to explain why increasing ST and decreasing GT are also traditionally observed – though to a lesser extent – when reward probability is 100% [21]. In this case, there is no reason in food-deprived animals for the magazine to become less attractive over training sessions. A second interpretation, proposed by Pearce and Hall [42], suggested that the acquisition of a CS–UCS association not only depends on the ability of the CS to predict the UCS, but also on the ability of the CS to indicate a change (inconstancy) in the reinforcement contingency relative to previous trials. The greater attention to the lever CS posited by the Pearce-Hall model is consistent also with an enhancement of incentive salience as a motivational/perceptual process. Given that this model is related to learning and that mesocorticolimbic activation and mesolimbic dopamine is implicated in ST [21], some observers might still take a purely learning-based interpretation. For instance, Fiorillo et al. [18] raise the possibility that 'dopamine could facilitate attention and learning in accord with the Pearce-Hall theory'. However, as discussed below, there is evidence that dopamine controls incentive motivation more than learning, and that stronger ST is induced by stronger motivation rather than simply by stronger learning. It is worth discussing additional theoretical conceptions in light of the present results.

A first hypothesis suggests that reward uncertainty promotes information seeking through exploration [1,30]. For instance, there is evidence that animals prefer working to receive food rather than consuming the same food from a freely available source [3,23], and the exploration of a novel environment – a situation that represents a form of uncertainty – is correlated with the release of mesolimbic dopamine in the brain [29]. Although a 'need to know' through exploration is assuredly a powerful source of motivation in some circumstances, it is unlikely to explain our results. To begin with, the increased activity levels exhibited during a phase of exploration have a limited time course and steadily tend to decrease over a period of continuous exposure to unknown objects or events, or over repeated exposure to them – a process referred to as habituation [33]. In contrast, the different behavioral expressions of ST increase over repeated exposure to the CS lever until reaching plateaus with high values maintained over time (see also [2]). Furthermore, contrary to the information-seeking hypothesis, goal-trackers are known to learn the predictive value of CSs as well as sign-trackers – they just do not develop a 'fascination' for CSs [20]. In accordance with these suggestions, the presence of a nose-poke

hole in autoshaping chambers seems to attract sign- and goal-trackers in a similar way, suggesting that sign-trackers are not more inclined to explore their environment than goal-trackers [20].

A second hypothesis interprets the effects of reward uncertainty in terms of prediction error, which is assumed to represent the degree of learning on a task [50,51]. Indeed, a series of impressive electrophysiological studies by Schultz and colleagues indicate that midbrain dopamine is released when the learning of a CS–UCS association is in progress (prediction error $\neq 0$) and ceases as soon as the learning process is completed (prediction error = 0). In addition, sustained midbrain activation of dopamine neurons [18] and striatal utilization of dopamine [34,44] reflect a quadratic function, where dopamine signal is higher under a 50% probability of reward (i.e. when error is maximal) than under either 25% or 75%, and similar to baseline when reward probability is 0% or 100% (i.e. when error is nil). Assuming that this view is correct, it could be argued that lever attractiveness in our two experiments simply denotes the inability of rats to predict future outcome – increased attractiveness occurring under persistent error signal or unpredictability [51]. However, a number of studies involving Pavlovian associations suggest that there is more than learning involved in ST and in the motivational magnet power of the CS lever. For instance, sign-trackers and goal-trackers do not differ in their ability to learn Pavlovian associations, while the former produce more dopamine than the latter and react to lever presentation in a much more vigorous way [21]. There is a body of evidence to suggest that variations in dopamine levels induce an instant shift in CS-directed behaviors in animals that have received identical training on a task [7,14,37,49].

A third hypothesis consists of considering reward uncertainty as a source of stress. Broadly, stress occurs when there is a discrepancy between an environmental/bodily demand and an individual's ability to satisfy that demand [5]. Uncertainty can be a source of stress, as it makes the ability to satisfy a demand harder. Although stress is typically known to be aversive and to induce freezing or flight, there is empirical evidence that stress may have positive motivational effects. For instance, stress has been shown to facilitate brain stimulation reward [32] and to cause dopamine release in the nucleus accumbens [41]. Interestingly, microinjections into the shell region of the nucleus accumbens of corticotropin-releasing factor (500 ng) – often referred to as a stress neurotransmitter – or amphetamine (20 μg), increase cue-triggered motivation for sucrose reward in a similar way [43]. Similarly, reward uncertainty produced by a variable rather than a fixed ratio schedule leads to a heightened locomotor response to a low dose of amphetamine [53], suggesting an impact of uncertainty on the dopaminergic system. In autoshaping, sign-trackers are known to produce more dopamine, and possess higher corticosterone levels, than goal-trackers [19,58]. And rats reared under isolated (stressful) conditions display a greater propensity to sign-track and exhibit more elevated corticosterone levels than rats reared in enriched (calming) conditions [4,35].

A fourth hypothesis we suggest posits uncertainty to *directly* amplify the level of incentive salience attributed to a discrete CS, via potentiating mesocorticolimbic reactivity, to make the lever CS more attractively 'wanted' as a motivational magnet [59]. If so, uncertainty may act somewhat similar to neurochemical stimulation of mesocorticolimbic circuitry, for example elevating neuronal firing and motivational attraction to a CS [14,18,37,49,55,56]. Mesocorticolimbic reactivity to cues acts as a positive gain factor to directly elevate incentive salience generated from the previously learned value at the moment of CS re-encounter [59], and so can increase sign-tracking [14,37]. The incentive salience hypothesis is based in part on evidence that mesolimbic dopamine release causes 'wanting', and different parameters – such as drugs, neural sensitization, and appetites – have been shown to affect the

expression of 'wanting' [8,49]. These parameters are able to act in a multiplicative way, as shown by Tindell et al. [56], where the incentive motivational power of acute amphetamine and sensitization are stronger in combination than either factor alone [59]. It is reasonable to think that reward uncertainty acts similarly, adding its incentive effects to those of other parameters (e.g. [53]). Given the incentive motivational effect of reward uncertainty, it might act as a kappa factor to enhance mesocorticolimbic reactivity to the CS in a computational model such as Zhang et al.'s [59]. It is important to note that the stress hypothesis mentioned above is also compatible with incentive salience if we consider its ability to alter dopamine levels or mesocorticolimbic reactivity in the brain.

In short, the uncertainty about reward delivery induced by our procedure might have enhanced the reactivity of brain motivation circuits to cause more incentive value to be attributed to the reward cue and led more individuals to become sign-trackers. The stress or motivation hypothesis can also explain why the response plateaus do not decrease over time, contrary to the prediction of the information-seeking hypothesis. It may also explain why sign-tracking increases in proportion to the degree of CS–UCS unpredictability. Further investigations will be required to test the relative roles of direct incentive salience modulation or stress as psychological processes behind the increase in incentive motivation attributed to cues associated with reward uncertainty.

Acknowledgments

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