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OBSERVATION

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Learning from rewarding and aversive outcomes shapes how sensory signals are processed by the attention system, reflecting a consequence of selection history. Substantial evidence points to Pavlovian associative learning as the mechanism by which previously reward-associated and aversively conditioned stimulus features gain attentional priority. On the basis of differences between reward-dependent feature-based and space-based attentional biases, it has been suggested that reinforcement learning underlies the influence of selection history on spatial attention. By pairing the orienting of overt spatial attention with aversive electric shock, we provide direct evidence that Pavlovian learning between locations and outcomes can shape spatial attention.

Public Significance Statement
We learn from prior experience what to direct our attention to. Exactly how we learn to direct our attention is unclear. In the present study, we provide novel evidence for an influence from Pavlovian learning in the control of spatial attention. A better understanding of how learning influences attention is important for the ability to effectively train attention and understand how maladaptive patterns of attention develop.

Keywords: spatial attention, selection history, aversive conditioning, associative learning

What we pay attention to is the joint product of our current goals and intentions, the physical salience of different stimuli in our environment, and our learning history (Wolfe & Horowitz, 2017). In theories of attentional control, *selection history* is often used as an umbrella term that encompasses the influence of learning from past experience broadly (Anderson et al., 2021; Awh et al., 2012). Reward learning and aversive conditioning are two more specific aspects of selection history that have been examined in the study of attention, especially with respect to feature-based attention. In this context, an important question concerns the nature of the learning mechanisms that are responsible for selection history-dependent attentional biases. When an object is reliably paired with a rewarding or aversive outcome during learning, individuals may preferentially attend to this object either because of its association with a valent and survival-relevant outcome (Pavlovian associative learning) or because orienting to it is reinforced by the procurement of reward or the opportunity to mitigate or potentially even avert an aversive outcome (reinforcement learning).

Although reinforcement learning likely plays some nonzero role in the case of feature-based attentional biases resulting from selection history, with attentional biases for reward-predictive stimuli being reduced in magnitude when orienting to such stimuli results in reward omission (Pearson & Le Pelley, 2020), there is now substantial evidence that Pavlovian learning mechanisms dominate the influence of reward learning and aversive conditioning on attention to stimulus features. In the case of reward learning, rewarding participants for finding targets of a particular color does not result in an attentional bias for that color unless the color provides unique predictive information about the magnitude of the upcoming reward (Sali et al., 2014), and stimuli for which participants are never rewarded for orienting toward nonetheless capture attention when predictive of reward as a task-irrelevant distractor (e.g., Bucker & Theeuwes, 2017; Le Pelley et al., 2015). In the case of aversive conditioning, participants will acquire attentional biases for shock-associated stimuli even when these stimuli are centrally presented during training and there is no behavior that could avoid shock (Schmidt et al., 2015), and participants will

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exhibit a bias to orient toward distractors associated with an aversive outcome even when this orienting response actually triggers the aversive outcome (Anderson & Britton, 2020; Mikhael et al., 2021). Compellingly, both previously reward-associated and previously shock-associated stimuli are more likely to draw eye movements as distractors even when the response required to earn money or avoid shock during training (that would be presumably reinforced by the contingencies) was to do the exact opposite and look away from these stimuli (Kim & Anderson, 2019, 2021).

The role of reward learning in the control of spatial attention has also been examined, in situations in which attending to a stimulus only when appearing in a particular spatial location (Bourgeois et al., 2018; Chelazzi et al., 2014; Della Libera et al., 2017; Mine et al., 2021; see also Anderson, 2015) or attending to a particular region of a scene (Anderson & Kim, 2018a, 2018b; Liao et al., 2021) results in high reward. In this case, there is evidence that attention is biased toward reward-associated regions of space (Anderson & Kim, 2018a, 2018b; Bourgeois et al., 2018; Chelazzi et al., 2014; Della Libera et al., 2017; Liao et al., 2021; Mine et al., 2021). Likewise, directional eye movements, divorced from a particular region of a scene, are potentiated when paired with reward (Liao & Anderson, 2020; see also McCoy & Theeuwes, 2018). In the case of aversive conditioning, pairing electric shock with a direction or amplitude of eye movement during free viewing of a scene results in a reduction in the frequency of the kind of eye movement that can trigger shock (Anderson, 2021).

When it comes to the influence of reward learning and aversive conditioning on attentional biases, there is an apparent dissociation between feature-based and space-based attentional biases with respect to the role of contingency awareness. The learning responsible for the influence of reward and aversive outcomes on feature-based attentional orienting can be implicit, being manifest in participants unaware of the stimulus—outcome contingencies (e.g., Grégoire & Anderson, 2019; Grégoire et al., 2021, 2020; Hopkins et al., 2016), including in studies that rigorously classified participants as unaware on the basis of evidence favoring the absence of awareness using a Bayesian approach (Leganes-Fonteneau et al., 2018, 2019). In contrast, there is evidence that reward-dependent spatial attentional biases are observed only in participants explicitly aware of the location—reward contingencies, with unaware participants showing no evidence of a bias toward the reward-associated location (Jiang et al., 2015; Mine et al., 2021; Sisk et al., 2020). A learning-dependent spatial attentional bias is robust in situations in which participants need to decide where to orient during training to obtain reward (Anderson & Kim, 2018a, 2018b; Liao et al., 2021; see also Liao & Anderson, 2020; Won & Leber, 2016), which likely facilitates explicit awareness of the contingencies (as evidenced by the choices participants make favoring the reward-associated region of space). There is at least one case of a bias in directional eye movements resulting from aversive conditioning in the absence of contingency awareness, but with the observed bias being against generating a saccade in the shock-associated direction (Anderson, 2021).

Collectively, these prior finding have been taken to suggest that, in contrast to feature-based attentional orienting, the influence of selection history on spatial orienting is governed chiefly by mechanisms of reinforcement learning (Anderson et al., 2021); when participants intentionally orient spatial attention in a manner that maximizes reward or minimizes aversive outcomes, they develop a bias to repeat such orienting behavior. However, prior reward studies do not provide a direct test in which Pavlovian learning makes unique predictions with respect to spatial attention, as participants are rewarded for the act of orienting in a particular direction, and so do not explicitly rule out an influence of Pavlovian learning. In the one study examining spatial attentional biases arising from aversive conditioning (Anderson, 2021), the aversive outcomes were paired with eye movements of a certain direction or amplitude rather than spatial locations, so there is nothing in the environment that could be associated with shock and influence attention by virtue of this association. A rigorous, direct test of whether Pavlovian learning between locations and outcomes can bias spatial attention is lacking. In the present study, using aversive conditioning, we provide a direct test of whether Pavlovian learning can shape spatial attention, which would predict a bias to orient *toward* locations previously associated with an aversive outcome.

Method

Participants

Forty participants were recruited from the Texas A&M University community (M_{age} = 19 years, 19 male, 21 female) and were compensated with course credit. All reported normal or corrected-to-normal visual acuity and normal color vision. All procedures were approved by the Texas A&M University Institutional Review Board. The recruited sample provided power $(1-\beta) > .80$ to detect an effect of size $d_z = .472$, taken from Liao and Anderson (2020), which is smaller than the effect size in other studies examining reward's influence on both overt and covert attention (Anderson & Kim, 2018a, 2018b; Chelazzi et al., 2014; McCoy & Theeuwes, 2018) and the influence of aversive conditioning on directional eye movements (Anderson, 2021). The recruited sample also provided power $(1-\beta) > .80$ to detect a correlation between attentional bias and awareness of the magnitude $r = .457$, which was the mean of the two correlations reported in the test phase of Grégoire and Anderson (2019), the study upon which the design of the awareness test was based.

Apparatus

A Dell OptiPlex equipped with Matlab software and Psychophysics Toolbox extensions (Brainard, 1997) was used to present the stimuli on a Dell P2717H monitor. The participants viewed the monitor from a distance of approximately 70 cm in a dimly lit room. Eye position was monitored using an EyeLink 1000-plus desktop mount eye tracker sampling at 1000 Hz. Head position was maintained using an adjustable chin and forehead rest (SR Research). Electric shocks were delivered through an isolated linear stimulator under the constant current setting (STMISOLA, BioPac Systems).

Stimuli and Task

Participants completed a simple visual search task in which they oriented to a diamond target among three nontarget circles (each stimulus approximately 3.85° × 3.85°); the shape stimuli were

located at the cardinal positions surrounding a central fixation cross, each at an eccentricity of approximately 9.5° (see Figure 1). Participants completed seven blocks of 80 trials each, with the target appearing equally often in each position in each block. Trials in each block were presented in a random order. Nine-point calibration was performed before each block, and the search stimuli would only appear after 500 ms of continuous fixation was acquired (eye position was manually drift corrected by the experimenter as needed to acquire initial fixation; see Anderson & Kim, 2019). Eye position was measured online and the search display terminated when eye position fell within a window extending approximately 1.9° beyond the boundary of the target for a continuous period of 50 ms or 1,000 ms had elapsed (after which the trial time out), whichever occurred first. The trial ended with a 1,000 ms blank intertrial-interval (ITI); in the event that participants did not fixate the target before the trial timed out, the word "Miss" was presented during the ITI. All stimuli were presented in white on a black background.

The first two blocks of trials served as baseline, in which the speed with which a target could be fixated at each of the four stimulus positions was measured. In Blocks 3–5, which served as the *training phase*, participants were connected to a linear isolated stimulator and informed that they would be periodically shocked as they performed the task. The intensity of the shock was individually calibrated to be unpleasant but not painful at the outset of the experiment using established procedures (e.g., Britton & Anderson, 2021; Grégoire et al., 2021, 2020; Kim & Anderson, 2020, 2021; Kim et al., 2021). In the event that the target appeared in the shock-associated location on a trial during the training phase (location counterbalanced across participants), a shock was delivered with 100% contingency right after the shape stimuli were offset, which occurred immediately upon registration of a target fixation (or a timeout in the event that no target fixation was acquired). Participants were not explicitly informed of this contingency but

Figure 1
Example Trial
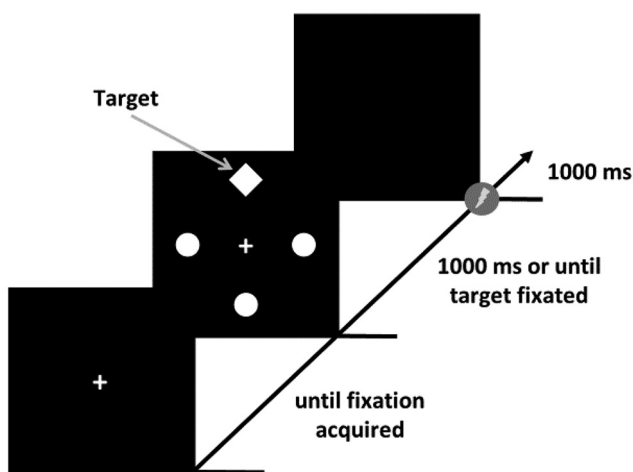
Note. Participants needed to fixate the diamond target within the 1,000 ms time limit. During the training phase (Blocks 3–5 of the task), a shock was delivered immediately after the shape stimuli offset (either a registered target fixation or a timeout) if the target had appeared in one of the four possible locations on the screen.

had to learn it from experience in the task. In the final two blocks of trials, which served as the *test phase*, participants were informed that shock was no longer possible and disconnected from the linear isolated stimulator.

At the end of the test phase, participants completed an assessment of their awareness of the shock—location contingencies (similar to Grégoire & Anderson, 2019; Grégoire et al., 2021, 2020). They were presented with 16 trials, with the target appearing equally often in each of the four locations. On each trial, participants were asked to indicate how likely they thought they would be to receive a shock for orienting to the target if they had seen this trial during the portion of the experiment in which shocks were delivered, by clicking on a scale from 0–100.

Data Analysis

The time to fixate the target was measured from the onset of the shape stimuli on each trial. For each phase, we computed the baseline-corrected response time (RT) to fixate the target for each of the four stimulus positions by subtracting the baseline measure from the measure obtained from each phase of the task, with positive differences meaning that participants were slower during the respective phase than during baseline and vice versa for negative differences. This baseline correction accounts for any systematic differences in the speed with which participants can orient in a particular direction irrespective of learning in the task (see McCoy & Theeuwes, 2018). Finally, the baseline-corrected RT for the three locations not paired with shock were averaged for each participant and compared with the baseline-corrected RT for the shock-associated location in each phase. A Pavlovian learning account predicts that participants will orient more quickly to targets appearing at the location associated with shock, reflecting elevated attentional priority given to that region of space. Opposite results might be expected from punishment learning, with participants being slower to orient to the location for which their response will result in the immediate delivery of an aversive outcome. We also examined the likelihood that the first stimulus fixated was a nontarget (errant fixation) as a function of whether the location of the target was associated with shock.

Two measures of awareness of the shock–location contingencies were computed, one continuous and one categorical. The continuous measure was computed as the difference between the mean perceived likelihood of shock when the targeted appeared in the shock-associated location minus the mean of when it appeared in one of the other three locations (maximum value of 100, with negative values indicating that participants thought shock was more likely at locations not actually associated with shock), which was used in correlation analyses. We also sought to classify participants as aware or unaware while avoiding pitfalls concerning the use of null hypothesis significance testing in which nonsignificant evidence in favor of awareness is taken to suggest a lack of awareness (see Leganes-Fonteneau et al., 2018; Vadillo et al., 2016). To this end, we computed the Bayes Factor (BF) over the difference in self-reported perceived likelihood of shock between when the target appeared in the shock-associated location versus the other three locations. Participants with a BF > 3 in favor of the alternative hypothesis *shock-associated > other* were scored as aware, participants with a BF > 3 in favor of the null hypothesis were

scored as unaware, and participants with a BF between these two cutoffs were scored as insensitive with respect to awareness.

Conditional means were computed from the raw data using Matlab, t tests and correlations were conducted using SPSS 26, and Bayes Factors were computed using JASP 0.11.1.0 using the default priors. Effect sizes were computed in Microsoft Excel.

Data Availability

Raw data and experiment code are available via the Open Science Framework (OSF) at https://osf.io/xn356/.

Results

Training Phase

Participants were significantly faster to orient to a target when appearing in the shock-associated location during the training phase compared with a location not associated with shock, $t(39) = -3.89$, $p < .001$, $d_z = .61$, $BF_{10} = 71.92$. As a continuous measure, awareness was significantly correlated with the attentional bias toward the shock-associated location, with participants more aware of the contingencies showing stronger attentional effects, $r = -.435$, $p = .005$, 95% confidence interval (CI) [.1428, .6574], $BF_{10} = 8.82$ (see Figure 2). Overall, 30/40 participants were scored as being aware of the shock—location contingencies, 2/40 as unaware, and 8/40 as insensitive. When the 30 aware participants were analyzed separately, the mean attentional bias in favor of the shock-associated location was significant, $t(29) = -4.61$, $p < .001$, $d_z = .84$, $BF_{10} = 335.87$, but this was not the case for the remainder of participants (unaware and insensitive), $t(9) = -.05$, $p =$

.962, $d_z = .02$, $BF_{10} = .31$. Timeouts occurred very infrequently and did not differ based on whether the target appeared in the shock-associated location versus a different location (.9% vs. .7%, respectively, $p = .602$). Participants initially fixated a nontarget on 5.4% of trials and were less likely to do so when the target appeared in the shock-associated location (3.2%) versus a location not associated with shock (6.2%), $t(39) = -2.77$, $p = .008$, $d_z = .44$, $BF_{10} = 4.70$. When the target appeared in a location other than the shock-associated location, 48.7% of errant fixations were on nontargets appearing in the shock-associated location, which was significantly greater than unbiased selection (1/3) via a binomial test ($p < .001$).

Test Phase

In the test phase, the RT difference between the previously shock-associated location and other locations was no longer significant, $t(39) = -1.26$, $p = .214$, $d_z = .20$, $BF_{10} = .36$. However, the correlation between attentional bias and awareness remained significant, $r = -.465$, $p = .002$, 95% CI [.1795, .6783], $BF_{10} = 16.25$ (see Figure 2). For aware participants, an attentional bias toward the shock-associated location was still evident, $t(29) = -2.86$, $p = .008$, $d_z = .52$, $BF_{10} = 5.53$, while for the remainder of participants (unaware and insensitive), the bias was not sensitive and numerically in the other direction, $t(9) = 1.72$, $p = .120$, $d_z = .54$, $BF_{10} = .93$. Timeouts occurred very infrequently (.6%) and again did not differ based on the location of the target ($p > .999$). Participants initially fixated a nontarget on 5.9% of trials and were less likely to do so when the target appeared in the shock-associated location (3.5%) versus a location not associated with shock (6.7%), $t(39) = -2.45$, $p = .019$, $d_z = .39$, $BF_{10} = 2.36$. When the target appeared

Figure 2
Behavioral Data
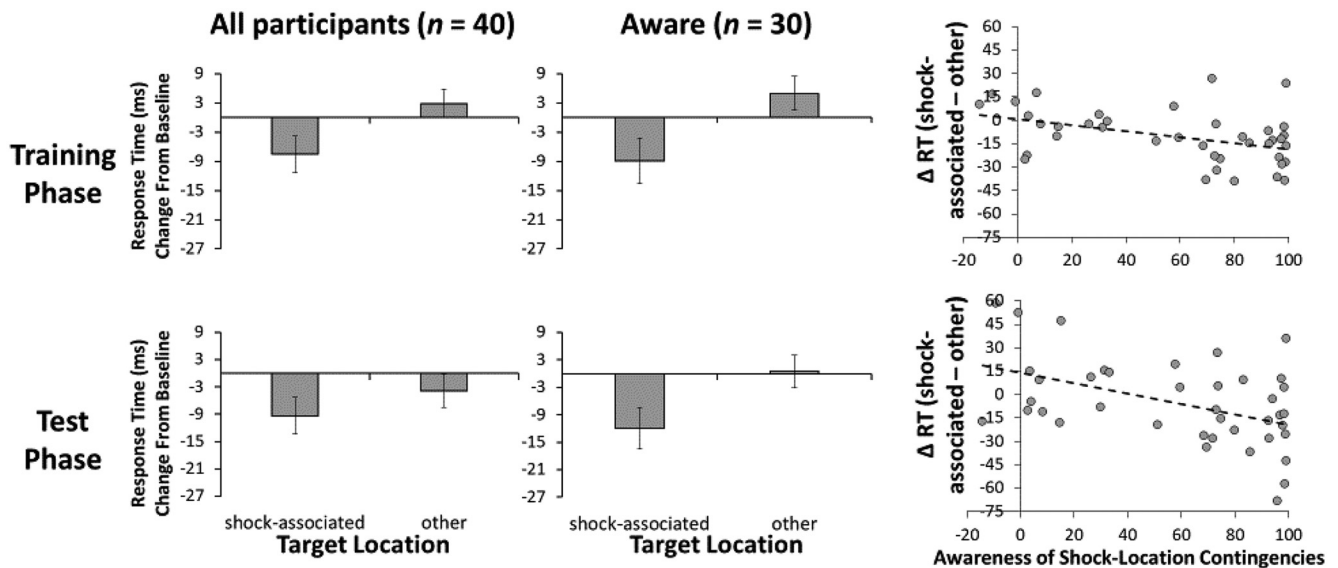
Note. The bar graphs depict baseline-corrected response time (RT) to fixate the target when appearing in the shock-associated location versus a different location separately for all participants and participants who were scored as aware of the shock—location contingencies. Error bars reflect the *SEM*. The scatter plots depict the correlation between awareness of the shock—location contingencies and the magnitude of attentional bias in favor of the shock-associated location (RT difference between the two location conditions).

in a location other than the shock-associated location, 50.8% of errant fixations were on nontargets appearing in the shock-associated location, which was significantly greater than unbiased selection (1/3) via a binomial test ($p < .001$), mirroring the pattern from the training phase.

Discussion

Our findings provide straightforward evidence that Pavlovian learning contributes to the influence of selection history—and more specifically aversive conditioning—on the control of overt spatial attention. Participants were in general biased to orient more quickly to targets appearing at the location with which orienting to such stimuli was associated with shock, even though this orienting response would immediately trigger shock during the training phase. This bias was correlated with awareness of the shock—location contingencies and significant only for aware participants, for whom it persisted into the test phase. Across both the training and test phases, nontargets were more likely to be erroneously fixated when appearing at the shock-associated location, again even though fixating a target at this location resulted in immediate shock during the training phase. The inclusion of a test phase in which the shock—location contingencies were removed, and indeed participants were disconnected from the electrical stimulator to make it abundantly clear that shocks were no longer possible in the task, clarifies that the observed attentional biases reflect selection history (Anderson et al., 2021; Awh et al., 2012) rather than the consequence of strategic attentional control such as overt threat monitoring.

These findings are consistent with previous studies demonstrating that spatial attentional biases arising from reward learning are contingent upon awareness of the reward contingencies (Mine et al., 2021; Sisk et al., 2020; see also Anderson & Kim, 2018a, 2018b; Liao et al., 2021), which contrasts with the influence of reward learning and aversive conditioning on feature-based attention that can be implicit (Grégoire & Anderson, 2019; Grégoire et al., 2021, 2020; Hopkins et al., 2016; Leganes-Fonteneau et al., 2018, 2019), suggesting a fundamental difference between how selection history shapes feature-based and space-based attentional biases. Like feature-based attentional biases arising from both reward learning and aversive conditioning, however, Pavlovian learning is implicated, which may reflect a broad principle in the selection history-dependent control of attention.

An intriguing question that the present study reinvigorates concerns the apparent dissociation between learning-dependent feature-based and space-based attentional biases with respect to the importance of contingency awareness. Why would the influence of location—outcome relationships on attention be so strongly dependent upon contingency awareness while the influence of stimulus—outcome relationships on attention is not (e.g., Grégoire & Anderson, 2019; Grégoire et al., 2021, 2020; Hopkins et al., 2016; Leganes-Fonteneau et al., 2018, 2019)? Although uncovering the answer to this question will undoubtedly require additional research, one possibility, as hypothesized by Anderson et al. (2021), is that the influence of selection history on the control of attention is contingent upon attention to the outcome-predictive feature or attribute during learning. This is what allows the predictive feature or attribute to be represented in the perceptual system with the fidelity necessary to be linked with the associated outcome. Such an account could explain why attentional capture by a previously reward- or punishment-associated feature is typically observed when this feature is either target-defining during learning (and is preferentially attended by virtue of goal-directed attention mechanisms) or physically salient (and is preferentially attended via stimulus-driven attention mechanisms). To the degree that participants tend to exclusively focus their attention on the target-defining feature (diamond) in the present study, they may not represent the location of the target with the fidelity necessary to pair that representation of location with reward. Participants who explicitly note the location of the target may be more likely to become aware of the relationship between one particular location and shock, and also represent that location robustly enough for it to be linked with the outcome that follows (see Anderson, 2017).

The present study does not lend itself to conclusions about how information is processed in the absence of awareness, as only two participants could be sensitively classified as unaware of the shock—location contingencies based on their responses in the assessment of awareness. Insensitive participants are uninformative with respect to issues of awareness. We restrict our conclusions to participants who are aware of the contingencies. Given the fairly high rate of awareness in the present study, a study aimed at understanding spatial attentional biases in the absence of contingency awareness might use contingencies that are more probabilistic with respect to location (e.g., 80/20). Although awareness was generally quite high in the present study, it likely reflects a conservative estimate given that it was based on a retrospective assessment probing memory for task contingencies that was also characterized by a low number of trials and the need to process task instruction between the training phase and completion of the assessment (see Leganes-Fonteneau et al., 2022; Lovibond & Shanks, 2002; Mertens & Engelhard, 2020; Vadillo et al., 2020). Future studies could employ more sensitive assessments of awareness that are more integrated into the learning task itself (see Leganes-Fonteneau et al., 2018, 2019, 2022), relying on evidence in favor of equivalency across conditions with respect to predicted outcomes (Leganes-Fonteneau et al., 2021; see also Dienes, 2015; Shanks, 2017).

It is also important to note that our findings do not rule out a role for reinforcement learning in the selection history-dependent control of attention. Indeed, the findings of Anderson (2021) are best explained by appealing to a reinforcement learning mechanism, although that study focused specifically on the potential role of negative reinforcement learning and, given the design of the study, there were no associations between aversive outcomes and any particular region of space that could have been learned in the task. Our findings make clear that Pavlovian learning *can* influence the selection history-dependent control of overt spatial attention, using a task in which a location at which a target can appear is associated with an aversive outcome. It is also important to note that our task specifically examines overt rather than covert spatial attention and that our findings might not generalize to covert spatial attention.

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