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Secondary visual cortex is critical to the expression of surprise-induced enhancements in cue associability in rats

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Abstract

Considerable evidence indicates that reinforcement prediction error, the difference between the obtained and expected reinforcer values, modulates attention to potential cues for reinforcement. The surprising delivery or omission of a reinforcer enhances the associability of the stimuli that were present when the error was induced, so that they more readily enter into new associations in the future. Previous research from our laboratory identified brain circuit elements critical to the enhancement of stimulus associability by the omission of an expected event and to the subsequent expression of that altered associability in more rapid learning. A key finding was that the rat posterior parietal cortex was essential during the encoding, consolidation, and retrieval of associability memories that were altered by the surprising omission of an expected event in a serial prediction task. Here, we found that function of the adjacent secondary visual cortex was critical only to the expression of altered cue associability in that same task. This specialization of function is discussed in the context of broader cortical and subcortical networks for modulation of attention in associative learning, as well as recent anatomical investigations that suggest that the rodent posterior parietal cortex overlaps with and may subsume secondary visual cortex.

Keywords

attention; associative learning; prediction error; Pearce-Hall theory

Introduction

Previous research from our laboratory identified brain circuitry critical to the enhancement of stimulus associability by the omission of expected events (Holland & Maddux, 2010). Much of this research used a *serial prediction task* (Table 1) in which the surprise-induced recalculation of cue associability and its expression as faster learning are widely separated in time. Transient manipulations in a structure's activity at the time of surprise or when the rate of new learning is tested can distinguish between that structure's contributions to these two functions. We have used this strategy to identify several regions that uniquely contribute to associability recalculation or to its expression in more rapid learning (Holland & Schiffino, 2016). However, we found only one region, the posterior parietal cortex (PPC), whose

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function was required both when associability changes were encoded and when they were retrieved for new learning, and hence was a likely substrate for memories of altered cue associability (Schiffino, et al., 2014). Infusions of the α -amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid (AMPA)-type glutamate receptor antagonist 1,2,3,4-tetrahydro-6-nitro-2,3-dioxo-benzo[f]quinoxaline-7-sulfonamide (NBQX) into PPC prior to either surprise or test sessions eliminated the usual enhancement of learning rate by prior surprise. Furthermore, that enhancement was also eliminated if the protein synthesis inhibitor anisomycin was infused into PPC soon after surprise sessions.

Although by virtue of its influential role in human attention and its demonstrated importance to surprise-induced associability enhancements (Bucci, et al., 1998; Maddux, et al., 2007), PPC is an attractive candidate site for encoding, consolidation and retrieval of altered associability memories, diffusion of NBQX into adjacent secondary visual cortex (V2) may have contributed to Schiffino et al.'s (2014) results. Indeed, given that visual target cues were used in the serial prediction task, V2 seems a highly plausible substrate for associability memories. Rodent visual cortex supplements collicular orienting to visual stimuli, and many effects attributed to the attentional modulation of primate visual cortex are also observable in rodent (Briggs et al., 2013; Gilbert & Li, 2013; Liang et al., 2015; Niell & Stryker, 2010; Pinto et al., 2013; Zhang et al., 2014). Although some investigators identify V2 as anatomically distinct from PPC (Kolb, 1990; Palomero-Gallagher & Zilles, 2015), the two interconnected regions share many afferents and efferents (Chandler et al., 1992; Reep et al., 1994; Wilber et al., 2015; Bota et al., 2015), have overlapping functions (e.g. Torrealba & Valdes, 2008; Wilber et al., 2014), and mapping of rodent visual cortex suggests that some visuotopic subdivisions straddle PPC-V2 borders (Palomero-Gallagher & Zilles, 2015; Swanson, 2004; Wang & Burkhalter, 2007; Garrett et al., 2014; Paxinos & Watson, 2014).

Here we evaluated the hypothesis that whereas rat PPC serves as a *source* of visual attention bias signals, V2 acts as a *site* to manifest that bias at the time of new learning (Broussard, 2012; Nobre & Mesulam, 2014), amplifying the integration of particular visual representations into new associative learning. We duplicated Schiffino et al.'s (2014) studies, infusing NBQX before either surprise (experiment 1) or test (experiment 2) sessions, but targeting V2, 1–1.5 mm posterior to PPC.

Materials and Methods

Subjects

Eighty male Long-Evans rats (Charles River Laboratories, Raleigh, NC) were used in this study: 32 in experiment 1 and 48 in experiment 2. Rats weighed 300–325 g upon arrival to the laboratory vivarium, and were given free access to food and water prior to surgery. Surgery was followed by 10–14 days of recovery before behavioral training. During the recovery period, the rats were handled daily. After recovery, they were food restricted to reach and subsequently maintain 85% of their free feeding weights throughout the course of the study. Rats were individually housed in a colony room with a 12:12 hr light-dark cycle. The care and experimental treatment of rats was conducted according to the National

Institutes of Health's *Guide for the Care and Use of Laboratory Animals*, and protocols were approved by the Johns Hopkins University Animal Care and Use Committee.

Apparatus

The behavioral training apparatus was the same as in Schiffino et al. (2014), and consisted of four separate chambers ($22.9 \times 20.3 \times 20.3$ cm). Each chamber had aluminum front and back walls, clear acrylic sides and top, and a floor of stainless steel rods (0.48 cm in diameter spaced 1.9 cm apart). A recessed food cup was located in the center of the front wall 2 cm above the floor, and was fitted with phototransistors to detect head entries. Two 45-mg sucrose pellets (Formula 5TUT, Test Diets, St. Louis, MO) delivered to the food cup served as the reinforcer. The light conditioned stimulus (CS) was generated by illumination of a 6-W panel lamp with a translucent covering, mounted 15 cm directly above the food cup. A 1500-Hz, 80-dB tone CS was presented via a speaker mounted on the inside wall of a sound-attenuating box that surrounded each chamber.

Surgery

Rats were anesthetized with 2–3% isoflurane mixed with oxygen and placed into the stereotaxic apparatus (Kopf Model 902, Tujunga, CA). After incision and craniotomy, four 1/8" self-tapping mounting screws were installed into the skull. Then, the dura was punctured with a 27-gauge needle and a 26-gauge guide cannula (PlasticsOne, Roanoke, VA), with stainless steel tubing cut to extend 3.5 mm below the 8.0 mm long pedestal, was implanted into each V2 at -5.3 mm posterior and ± 3.1 mm lateral to bregma, to a depth of 0.9 mm below the skull surface. These coordinates differed only along the rostrocaudal axis from those used for PPC cannulations in Schiffino et al. (2014). Cannulae were held in place with dental acrylic and fitted with obturators that were cut to match the length of the guide. Once the acrylic set, the incision was closed with surgical staples and topical antibiotic ointment was applied to the wound edges. Then, all rats received subcutaneous 0.02 mg/kg injections of sterile buprenorphine HCl (Sigma, St. Louis, MO) to ameliorate pain.

Behavioral training procedures

Prior to behavioral training, food-deprived rats were given 10 sucrose pellets in their home cages to familiarize them with the reinforcer, and the next day were trained to eat sucrose pellets from the recessed food cups in a single 64-min session, which included 16 unsignaled reinforcer deliveries. Table 1 provides an outline of the subsequent behavioral training procedures. Each training session in each phase of the experiments was 64 min in duration, and included 16 trials, distributed across random intertrial intervals, which averaged 4 min (range = 2 to 6 min). Training sessions were given daily, at approximately the same time each day. In the first, expectancy, phase, all rats received trials consisting of a 10-s light $\rightarrow$ 10-s tone serial compound, to establish a strong light-tone association. In each session of this phase, half of the 16 trials had the light $\rightarrow$ tone compound reinforced with sucrose pellets and the other half were non-reinforced. Trial order in each session was randomly determined. After 15 sessions of expectancy training, rats were allocated into performance-matched "shift" and "consistent" groups, and given 2 surprise phase sessions. During each surprise session, light $\rightarrow$ tone prediction error was induced for the shift rats by omitting the tone on the 8 nonreinforced trials, while consistent rats had their light $\rightarrow$ tone expectancies

confirmed through continuation of the expectancy protocol. Finally, in each of the 5 sessions in the test phase, all rats received 16 presentations of the light CS alone followed immediately by sucrose pellet reinforcement. Greater (and more rapid) acquisition of food-cup responses to the light CS was taken as evidence of relatively greater associability values. If induction of a prediction error in the shift rats enhanced the associability of the light cue, then those rats would acquire conditioning more rapidly in this test than rats in the consistent condition.

Behavioral measure and statistical analysis

The response measure was the percentage of time spent in the food cup, as assessed by interruption of the infrared photobeam. Trial epochs were defined as a 5 s stimulus-free pre-CS period (immediately prior to the light CS), the first 5 s of the light CS, the second 5 s of the light CS, the first 5 s of the tone CS, the last 5 s of the tone CS, and the 5 s initiated by reinforcer delivery. Conditioned food cup responding was assessed during the latter half of CS presentations because in that epoch, food cup CRs are more frequent and less contaminated by conditioned orienting behaviors (Holland, 1977).

Responding during the pre-CS, light, and tone (when applicable) epochs were each analyzed with separate ANOVAs with behavioral condition (shift or consistent), and drug treatment (NBQX or saline infusions) as between-subject variables, and repeated measures on the within-subjects variable of sessions (test phase) or session blocks (expectancy phase). The Greenhouse-Geisser procedure was used to correct for violations of sphericity; estimates of sphericity (ϵ) are provided when relevant. The critical analyses were those of the test data in each experiment. The effect of surprise on the light's associability would be revealed as a significant main effect of behavioral condition and a significant treatment X sessions interaction (which would demonstrate that the behavioral treatments not only affected the amount of responding over the whole test phase, but also the rate of learning over sessions), and modulation of those effects by NBQX infusions would be indicated by significant behavioral condition X drug treatment and behavioral condition X drug treatment X sessions interactions. In addition, ANOVAs of the test data were followed by planned contrasts to evaluate the hypotheses that behavioral treatment groups differed within each drug treatment (shift-vehicle vs. consistent-vehicle; shift-NBQX vs. consistent-NBQX) and that drug treatment groups differed within each behavioral treatment (shift-vehicle vs. shift-NBQX; consistent-vehicle vs. consistent-NBQX).

Drugs and infusion procedures

The drug infusion procedures were identical to those used by Schiffino et al. (2014, experiments 1 and 2). Rats had their obturators removed and reinserted before each of the expectancy sessions to familiarize them with manipulation of their cannula headsets. Two 33-gauge injector cannulae that extended 0.4 mm below the tip of the guide were connected by PE50 tubing to separate 10- μ L Hamilton syringes in a multiple-syringe pump (KD Scientific, Holliston, MA). The pump simultaneously administered 0.5 μ L of infusate bilaterally into V2, over one minute. After infusion, the injector was left in place for an additional minute. After removal of the injectors, the obturators were reinserted. In both experiments, V2 AMPA neurotransmission was perturbed by NBQX. NBQX (Sigma) was

dissolved at a concentration of 20 µg/µL in 0.1 M PBS vehicle. Infusions of NBQX were delivered within 20 minutes prior to the onset of each surprise session (experiment 1) or each test session (experiment 2). Vehicle rats in each behavioral condition received infusions of PBS.

Preliminary studies in which these volumes of dyes were infused into cortex suggested a spread that was mostly confined to the target region. That suggestion was corroborated by recent comparison of the behavioral effects in this task of infusions of NBQX or fluorescent muscimol (whose spread was verified) into a different brain region (the amygdala central nucleus, CeA; Schiffino & Holland, 2016). However, as we note in the *Discussion*, the primary basis for our claim that the spread of infusate was limited was our observation of a different pattern of results after infusions of NBQX into V2 and into the adjoining PPC in a previous study (Schiffino, et al., 2014).

Histological procedures

After completion of behavioral testing, the rats were deeply anesthetized with isoflurane and perfused intracardially with 0.9% saline followed by 3.7% formalin solution. Once fixed, brains were removed and stored at 4°C in 3.7% formalin 12% sucrose solution. Brains were sliced on a freezing microtome and 40-µm coronal sections were taken in series. To confirm cannula tip placements in the bilateral V2, every third section was mounted on glass slides, dehydrated in ascending concentrations of alcohol, defatted in xylene, and stained with thionin. Slides were coverslipped using Permount thinned with xylene, and examined with a light microscope.

Results

Histological results

Of the 80 rats acquired for the study, the data from 6 were excluded. In experiment 1, one of the 32 rats was excluded because its headset detached. In experiment 2, 4 of the 48 rats were excluded after their headsets detached, and one rat was excluded for missed cannula placement. Assessments of cannula tip placements confirmed that V2 was the site of injection for all rats whose data were included for further analysis (Figure 1). In experiment 1, the final numbers of rats in the shift-NBQX, shift-vehicle, consistent-NBQX, and consistent-vehicle conditions were 8, 8, 8, and 7, respectively. In experiment 2, those sample sizes were 11, 10, 10, and 12, respectively.

Behavioral results

Figure 2 depicts food-cup responding during pre-CS, light, and tone measurement epochs sequentially across all three phases (expectancy, surprise, and test) of experiment 1 (Figures 2A and 2C) and experiment 2 (Figures 2B and 2D).

Expectancy phase—In this phase of the experiments, which occurred prior to any drug treatments in any condition, rats received light→tone trials, reinforced with food on half of those trials. In both experiments, all groups of rats acquired comparably high levels of food-cup responding to the tone while exhibiting minimal conditioning to the light (leftmost

portions of each panel of Figure 2). The results of separate subsequent behavioral condition (shift vs. consistent) x subsequent drug treatment (NBQX vs. vehicle) x three-session block (1–5) ANOVAs of responding during each measurement epoch (pre-CS, light, and tone) confirmed this assertion. Importantly, no evidence of a significant behavioral condition x drug treatment interaction was observed for any of the three epochs in either experiment (P s > .490), nor did those interactions change across blocks (P s > .426). Likewise, although responding changed significantly over session blocks (P s < .040), there were no significant main effects of subsequent behavioral condition (P s > .214) or subsequent drug treatment (P s > .341). In experiment 1, animals to be infused with NBQX initially demonstrated greater responding to the tone, but that difference disappeared by the third block (drug treatment x block interaction: $\epsilon = 0.63$, $F_{(4, 108)} = 3.58$, $P = .024$). In experiment 2, pre-CS responding diverged slightly between behavioral conditions over the last three blocks (behavioral condition x block interaction: $\epsilon = 0.83$, $F_{(4, 156)} = 2.66$, $P = .045$), whereby pre-CS responding by shift-allocated rats decreased while responding by consistent-allocated rats went unchanged. No other interactions with block were significant (P s > .378), and the negligible differences in tone and pre-CS responding described above were unlikely to affect the outcome of this study. Indeed, ANOVAs on means from the last two sessions of the expectancy phase did not find significant effects (P s > .314) or interactions (P s > .560) involving responding in any epoch for either experiment. Thus, all groups of rats within each experiment exhibited comparable behavior before we initiated the surprise phase.

Surprise phase—The bars in each panel of Figure 2 show food-cup response means ($\pm$ s.e.m.) collapsed across the two surprise phase sessions, in which the tone stimulus was unexpectedly omitted on nonreinforced trials in the shift rats. In experiment 1, some rats from both behavioral conditions received infusions of NBQX prior to each session, whereas the remaining rats received infusions of vehicle. Importantly, behavioral condition x drug treatment ANOVAs showed that there were no significant effects of drug treatment on pre-CS responding ($F_{(1, 27)} = .091$, $P = .765$), responding during the light ($F_{(1, 27)} = 1.57$, $P = .221$), or responding during the tone ($F_{(1, 27)} = 2.93$, $P = .098$). Furthermore, there were no effects of behavioral condition (P s > .520), and the critical behavioral condition x drug treatment interaction was not significant for any measure (P s > .884). In experiment 2, rats did not receive infusions of NBQX or vehicle until the test phase, but data from the surprise sessions were analyzed with subsequent (test) drug treatment included as a variable. No effects of subsequent drug treatment (P s > .454) or behavioral condition (P s > .408) were significant for responding during either cue, nor did those variables interact (P s > .502). Thus, for both experiments, rats in all groups began the test phase after showing similar levels of responding to both the light and tone during the surprise phase (as well as during the expectancy phase).

Test phase—The rightmost portion of each panel of Figure 2 shows the primary data of this study, the acquisition of food-cup responding to the light during the test phase. In experiment 1 (Figures 2A and 2C), rats in the shift condition acquired greater food-cup responding to the light than rats in the consistent condition regardless of whether NBQX or vehicle was infused prior to surprise phase sessions. A behavioral condition X drug treatment X session ANOVA showed a significant effect of behavioral condition ($F_{(1, 27)} =$

11.74, $P = .002$) and a significant behavioral condition X session interaction ($\epsilon = 0.42$, $F_{(4, 108)} = 3.81$, $P = .036$), but no significant effect or interactions involving drug treatment ($P > .443$). Planned contrasts confirmed that test responding to the light was significantly greater in shift rats than in consistent rats, within both vehicle ($P = .043$) and NBQX treatments ($P = .011$), but responding did not differ reliably between vehicle- and NBQX-infused rats within either the shift or consistent behavioral condition ($P > .416$).

By contrast, in experiment 2 (Figures 2B and 2D), infusions of NBQX prior to each test phase session eliminated the shift condition advantage in learning about the light. Although the behavioral condition x drug treatment interaction was only marginally significant ($F_{(1, 39)} = 3.91$, $P = .055$), the critical behavioral condition x drug treatment x session interaction was highly significant ($\epsilon = 0.80$, $F_{(4, 156)} = 4.63$, $P = .003$). Furthermore, vehicle-infused rats in the shift condition showed significantly greater responding than either vehicle-infused rats in the consistent condition ($P = .034$) or NBQX-infused rats in the shift condition ($P = .020$). Conversely, among NBQX-infused rats, responding of shift and consistent rats did not differ significantly ($P = .542$), and no significant difference was observed between vehicle- and NBQX-infused rats in the consistent condition ($P = .721$).

ANOVAs of pre-CS responding in the test phase of experiment 1 did not yield any reliable effects ($P > .381$) or interactions ($P > .119$). In experiment 2, a significant effect of session ($\epsilon = 0.82$, $F_{(4, 156)} = 5.11$, $P = .002$) interacted with behavioral condition ($\epsilon = 0.82$, $F_{(4, 156)} = 2.70$, $P = .044$), but no other effects ($P > .204$) or interactions were significant ($P > .301$). Importantly, the shift advantage for vehicle-infused rats was not obscured by the elevated levels of pre-CS responding observed in the consistent condition.

Discussion

Taken together with Schiffino et al.'s (2014) findings, the results of the current study dissociate the roles of PPC and V2 in surprise-induced enhancements of cue associability. Whereas Schiffino et al. (2014) found that PPC function was critical during both surprise and test phases of the serial prediction task, here we found that V2 function was essential at the time of test (experiment 2) but not during surprise sessions (experiment 1). This dissociation between the effects of surprise-phase NBQX infusion into V2 (experiment 1) and into the adjoining PPC (Schiffino et al., 2014, experiment 1) suggests that our infusions were appropriately limited in their spreads. Furthermore, this PPC-V2 dissociation is consistent with the results of a previous study of FOS expression in this same task (Bucci & McLeod, 2007). In that study, when FOS was assessed after a surprise phase session, rats in the shift condition showed enhanced FOS in PPC, but not in V2. Finally, it is important to recognize that although test-phase infusions of NBQX into V2 in experiment 2 eliminated the shift group advantage in light-food learning, those infusions did not significantly affect light-food learning in the consistent group. Thus, perturbations of V2 activity did not preclude the formation of light-food associations that underlie conditioned food-cup approach.

The Pearce-Hall (1980; see also Pearce & Mackintosh, 2010) model provides a comprehensive framework for the adjustment of cue associability through experience.

Within that model, once a stimulus is registered, computational networks generate a prediction, determine the inaccuracy of that prediction (prediction error) after the outcome of a trial is known, and then adjust the associability (learning rate) parameter accordingly, to bias attention in future opportunities for learning. In the serial prediction task used here, after phase 1 expectancy training, the light stimulus prompts anticipation of the tone. Then, during the surprise phase, processing networks must register the light, retrieve an expectation about the occurrence of the tone, compute the prediction error (surprise), use that computation to adjust the light's associability parameter value, and finally archive that updated value in memory. Notably, because in the serial prediction task, the altered associability of the light cue is assessed several days after its adjustment in the surprise phase, that memory must be relatively long-lived.

Schiffino et al. (2014) suggested that a network involving PPC performs each of those steps. The present results indicate a limited role for V2 within that network: V2 AMPA neurotransmission is critical only for enhanced learning about cues whose associability parameters have increased. Although traditionally V2 is assigned a role in feature extraction (e.g., Andermann et al., 2011; Marshel et al., 2011; Montero & Jian, 1995) and subsequent relay of that information to PPC and other areas, the lack of an effect of NBQX infusions into V2 during the surprise phase (experiment 1) indicates that a feature-rich identification of the light cue (which likely illuminated the entire visual field) from V2 was not essential to performance in this task. Presumably, during the surprise-phase encoding of altered associability memories in experiment 1, PPC received requisite visual information from other brain regions, such as superior colliculus (SC) by way of thalamic lateroposterior nucleus (LP; Bucci et al., 1999; Nakamura et al., 2015; Reep et al., 1994; Sefton et al., 2015; Tohmi et al., 2014), or V1 (Bota et al., 2015; Bourassa & Deschenes, 1995; Masterson et al., 2009; Reep et al., 1994; Sherman, 2012), rather than via V2.

The expression of enhanced cue associability in facilitated learning may be mediated by a cortico-basal ganglia rat attention network (Reep & Corwin, 2009) analogous to that of primates (Baluch & Itti, 2011; Clark et al., 2015; Miller & Buschman, 2013; Petersen & Posner, 2012). Using the serial prediction and related tasks, we have documented roles in this expression function for V2 (experiment 2), PPC (Bucci et al., 1998; Maddux et al., 2007; Schiffino, et al., 2014), the cholinergic substantia innominata/nucleus basalis magnocellularis (Bucci et al., 1998; Chiba et al., 1995; Holland & Gallagher, 2006), and the dorsolateral striatum (Asem et al., 2015). In addition, we have shown that PPC (Schiffino et al., 2014), the CeA (Holland & Gallagher, 2006) and the substantia nigra pars compacta (SNc; Lee et al., 2008) are critical to the recalculation of cue associability at the time of surprise. However, the network that supports alterations in cue associability may be much more extensive, involving other regions that have been implicated in orienting and visuospatial attention in rodents, such as subregions of prefrontal cortex, primary visual cortex (V1), various thalamic nuclei, SC, and several striatal subregions. For example, PPC and V2 both innervate thalamic reticular nucleus (TRN) (Coleman & Mitrofanis, 1996; Vertes et al., 2015), and both reciprocate connections with V1, thalamic LP (Agster & Burwell, 2009; Bota et al., 2015; Kamishina et al., 2009; Miller & Vogt, 1984; Reep et al., 1994; Takahashi, 1985), and medial agranular cortex (AGm), which includes a frontal orienting field that coordinates eye, head, and vibrissae movements to induce overt shifts of

attention (Crowne et al., 1986; Erlich et al., 2011; 2015; Sinnamon and Galer, 1984). Although the role of thalamic LP in rodent attention remains uncharacterized, its putative primate homolog, the pulvinar, as well as the adjacent TRN, are integral components of attention networks (Reep & Corwin, 2009; Petrof & Brown, 2010; Saalman & Kastner, 2011; Yu et al., 2009).

Likewise, PPC and V2 gain extrathalamic access to subcortical loops through efferents to medial SC and overlapping regions of dorsal striatum (DS) (Comoli et al., 2012; Dudman & Gerfen, 2015; Harvey & Worthington, 1990; McHaffie et al., 2005). Functions of rodent SC during visual orienting (Ngan et al., 2015; Zhao et al., 2014) are comparable to those of primates (Krauzlis et al., 2013). Although attentional functions are not typically ascribed to DS (e.g., Balleine & O'Doherty, 2010; but see Anderson et al., 2014; Hikosaka et al., 2000), mounting evidence suggests that subregions of rat DS are involved in visual orienting and shifts of attention (Agnoli & Carli, 2011; Aoki et al., 2015; Christakou et al., 2001; 2005; Chudasama & Robbins, 2006; Han et al., 1997; Rogers et al., 2001; Van Vleet et al., 2000), including those that occur in the serial prediction task (Asem et al., 2015; Esber et al., 2015). These DS subregions may converge on dorsocentral striatum (DCS), which receives converging inputs from PPC, V2, AGm, and LP (Kamishina et al., 2008; Reep et al., 2003; Reep & Corwin, 2009). Additionally, both PPC and V2 densely innervate posterior aspects of dorsomedial striatum (DMS). Through those projections, PPC and V2 might expedite the formation of light-food associations mediated by DMS activity (c.f., Corbit & Janak, 2010; Reig & Silberberg, 2014).

Neurobiological sources of attentional control, including PPC, broadcast signals to bias access of representations to other limited-capacity processes (Bisley & Goldberg, 2010; Gottlieb, 2014; Nobre & Mesulam, 2014; Petersen & Posner, 2012; Serences & Yantis, 2006). Frequently, that bias is achieved through feedback modulation of activity in sensory areas such as visual cortex because alterations to the relative strength, clarity, or vividness of sensorial representations affect their processing (c.f., Cooke & Bear, 2015; Poort et al., 2015; Titchener, 1908). Thus, it is plausible that memory representations of visual cue associability values in PPC, akin to the “attentional priority maps” or “salience representations” described by others (e.g. Bisley & Goldberg, 2010; Gottlieb, 2007), modulate activity in visual cortex at the time of new learning, influencing a subset of systems engaged by light-food conditioning to manifest enhanced associability values in facilitated learning. Notably, although most considerations of the modulation of attention emphasize relatively transient influences (but see, for example, Anderson et al., 2014) altered associability memories appear to be long-lived, with surprise today influencing learning rate days in the future. Thus, a better appreciation of the functions of attention networks likely will encompass many domains of cognitive processing, including learning and memory at many time scales.

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Abbreviations

AGm	medial agranular cortex
AMPA	α -amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid
ANOVA	analysis of variance
CS	conditioned stimulus
DCS	dorsocentral striatum
DMS	dorsomedial striatum
DS	dorsal striatum
LP	lateroposterior nuclei of thalamus
NBQX	1,2,3,4-tetrahydro-6-nitro-2,3-dioxo-benzo[f]quinoxaline-7-sulfonamide
PPC	posterior parietal cortex
SC	superior colliculus
TRN	thalamic reticular nucleus
V1	primary visual cortex
V2	secondary visual cortex

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Figure 1.

Schematic representation of injector cannula tip placements for rats included in experiments 1(A) and 2(B). The numbers on the right indicate distance (mm) from bregma along the rostrocaudal axis. For each placement, a single black dot of 50% opacity was drawn using Adobe Photoshop. Thus, darker areas indicate greater overlap.

Figure 2.

Mean ($\pm$ SEM) food-cup responding during pre-CS, light, and tone measurement epochs across the expectancy, surprise, and test phases of experiments 1 (panels A and C) and 2 (panels B and D). Rats received infusions of vehicle (panels A and B) or NBQX (panels C and D) into secondary visual cortex (V2) prior to both surprise phase sessions in experiment 1, or before each test phase session in experiment 2. During the expectation and surprise phases, rats in all groups acquired and maintained comparably high levels of food-cup responding to the tone while exhibiting minimal conditioning to the light. The right side of each graph depicts the acquisition of food-cup responding over the course of the five test phase sessions. The shift group advantage in test phase learning was unaffected by surprise phase perturbations of V2 activity (panels A and C) in experiment 1. However, in experiment 2, V2 function during the test phase was critical for shift animals to exhibit benefits induced by surprise in the previous phase (panels B and D). Asterisks (*) indicate significant ($P < .05$) differences in overall test responding between shift and consistent rats; in experiment 2, vehicle-infused rats in the shift condition (panel B, filled circles) also showed significantly more responding than NBQX-infused shift rats (panel D, filled circles). Critically, the behavioral condition $\times$ drug treatment $\times$ sessions interaction was significant in experiment 2 ($P = .003$) but not in experiment 1 ($P = .443$).

Table 1

Outline of Procedures

Behavioral treatment	expectancy phase	surprise phase	test phase
Shift	light→tone→food light→tone→nothing	light→tone→food light→nothing	light→food
Consistent	light→tone→food light→tone→nothing	light→tone→food light→tone→nothing	light→food

In experiment 1, rats received either NBQX or vehicle before each surprise phase session. In experiment 2, rats received either NBQX or vehicle before each test phase session. In the shift condition, the surprising omission of the tone on nonreinforced trials (bold type) should enhance the associability of the light, allowing it to acquire conditioning more rapidly in the final test phase than rats in the consistent condition.