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Retrospective Revaluation of Associative Retroactive Cue Interference

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Abstract

Two fear-conditioning experiments with rats assessed whether retrospective revaluation, which has been observed in cue competition (i.e., when compounded cues are followed with an outcome), can also be observed in retroactive cue interference (i.e., when different cues are reinforced in separate phases with the same outcome). Experiment 1 found that after inducing retroactive cue interference (i.e., X-outcome followed by A-outcome), nonreinforced presentations of the interfering cue (A) decreases interference with responding to the target cue (X), just as has been observed in retrospective revaluation experiments in cue competition. Using the opposite manipulation (i.e., adding reinforced presentations of A), Experiment 2 demonstrated that after inducing retroactive cue interference, additional reinforced presentations of the interfering cue (A) increases interference with responding to the target cue (X); alternatively stated, the amount of interference increases with the amount of training with the interfering cue. Thus, both types of retrospective revaluation occur in retroactive cue competition. The results are discussed in terms of the possibility that similar associative mechanisms underlie cue competition and cue interference.

Keywords

Cue interference; retrospective revaluation; associative interference; retroactive interference

Pavlov (1927) observed that when a stimulus that initially did not elicit any responding (conditioned stimulus; CS) was followed by a response-eliciting stimulus (unconditioned stimulus; US), the initially neutral stimulus came to elicit a response (conditioned responding; CR) consistent with the nature of the US. Subsequent research has found that conditioning of a second cue to the same US reduces responding to the first trained CS (see Miller & Escobar, 2002, for a review). These manipulations can be methodologically categorized with respect to whether the cues are presented together (i.e., cue competition) or in different sequential phases (i.e., cue interference) during training. Orthogonally and more generally, these interactions can be categorized with respect to whether the interacting stimuli are cues or outcomes (i.e., antecedent or subsequent events, respectively). Superimposition of these procedural manipulations yields a comprehensive 2×2 matrix (see Figure 1).

Cue competition (see Cell 1 of Figure 1) refers to the decrease in responding to a target cue observed when an associated cue (i.e., one that has been paired with the target cue) also has an association with the same outcome. Overshadowing and blocking are two well known examples of cue competition. Stimulus interactions of this sort have received the greatest amount of attention in learning research since the discovery of blocking (Kamin, 1968). Notably, the prominence of learning models designed specifically to account for overshadowing and blocking (e.g., Rescorla & Wagner, 1972) led investigators to focus their research primarily on competition between cues. Nevertheless, decrements in responding produced by competition between outcomes (see Cell 2 of Figure 1) have been reported (Esmoriz-Arranz, Miller, & Matute, 1997; Miller & Matute, 1998; Rescorla, 1980) and challenge models based on total error reduction such as that of Rescorla and Wagner. To date, few associative models of learning have been designed to account for outcome competition (but see Stout & Miller, 2007).

Outcome interference (see Cell 4 of Figure 1; also known as interference between subsequent events) refers to the decrease in responding to a target cue seen when that cue has been trained with one outcome in one phase and with a different outcome in a second phase. Counter conditioning, extinction, and latent inhibition are all examples of outcome interference. Finally, and the focus of this paper, cue interference (see Cell 3 of Figure 1, also known as interference between antecedent events) refers to the decrease in behavior to a target cue observed when the target cue has been associated with one outcome in one phase, and a second cue has been associated with the same outcome in a different phase (e.g., Matute & Pineño, 1998b). Note that the associative interference in both Cells 3 and 4 may be either proactive or retroactive (for a review of the early verbal literature learning concerning proactive and retroactive interference, see Slamecka & Ceraso, 1960). Proactive interference refers to the decrease in responding to the target cue at test when the interfering situation occurs before target training, while retroactive interference refers to the decrease in responding to the target cue at test when the interfering situation occurs after target training. Methodologically, the assessment of either type of interference depends on which cue is assessed for control of behavior at test. That is, proactive interference is indexed by the behavior governed by the second learned association, whereas retroactive interference is indexed by the behavior governed by the first learned association.

Parallel effects of analogous manipulations have been found among the four cells of the matrix in Figure 1. For example, recovery from interference has been found when testing takes place in a context not related with either of the interfering associations in both interference between outcomes (Cell 4 of Figure 1; e.g., ABC renewal after extinction; Bouton & Bolles, 1979) and between cues (Cell 3 of Figure 1; e.g., Miguez, Cham, & Miller, 2012). Commonalities have also been observed in the recovery from interference when a long retention interval is imposed between training and testing in both outcome interference (Cell 4 of Figure 1; e.g., spontaneous recovery from extinction, Pavlov, 1927) and cue interference (Cell 3 of Figure 1; e.g., Miguez, Cham et al., 2012). Additional parallels between cue and outcome interference are described in Escobar, Arcediano, and Miller (2001) and Escobar, Matute, and Miller (2001). Similarly, a number of parallels between cue and outcome competition have been noted (e.g., Esmoris-Arranz, et al., 1997). Comparisons between interference and competition have been far scarcer.

The current experiments evaluated whether select manipulations that affect responding in cue competition (Cell 1 of Figure 1) can also affect responding in cue interference situations (Cell 3 of Figure 1). Specifically, we assessed whether retrospective revaluation, which is often observed in cue competition, can also be observed in cue interference. Retrospective revaluation in cue competition refers to a change in the responding to a target stimulus as a result of further training of the target's competing stimulus. Retrospective revaluation can be

produced by additional reinforcement or nonreinforced presentations of the competing stimulus. For example, subsequent nonreinforced presentations of an overshadowing stimulus (e.g., Kaufman & Bolles, 1981; Liljeholm & Balleine, 2009; Matzel, Schachtman, & Miller, 1985; Shevill & Hall, 2004) and subsequent nonreinforced presentations of a blocking stimulus (e.g., Blaisdell, Gunther, & Miller, 1999; Boddez, Baeyens, Hermans, & Beckers, 2011; but see Dopson, Pearce, & Haselgrove, 2009) produce an increment or recovery in responding to the overshadowed and blocked stimuli, respectively. Similarly, in a relative validity design (Wagner, Logan, Haberlandt, & Price, 1968), recovery of responding to the less valid cue has been observed when the more valid cue for reinforcement was extinguished between training and testing (Cole, Barnet, & Miller, 1995). Retrospective revaluation by reinforcement of the competing (i.e., blocking) stimulus has also been reported in a backward blocking procedure, which takes the form of a decrease in control of behavior by the target stimulus (e.g., Denniston, Miller, & Matute, 1996; Miller & Matute, 1996). Moreover, both types of retrospective revaluation have been reported when the context competes with a partially reinforced cue (Miguez, Witnauer, & Miller, 2012). If analogous or similar mechanisms underlie the phenomena observed in Cells 1 and 3 of the matrix in Figure 1, one would expect to observe analogous behavioral effects of operational retrospective revaluation in cue competition and cue interference. However, the observation of retrospective revaluation in cue interference would challenge accounts of retrospective revaluation in cue competition that rely on the existence of a within-compound association between the interacting stimuli at the moment of test (e.g., Stout & Miller, 2007) because in a cue interference design the interfering and interfered-with cue have never been presented together. Thus, no association should exist between them. Similarly, evidence of cue interference itself challenges models of associative learning in which only stimuli presented together compete for the available associative strength that the US can support on that trial (e.g., Rescorla & Wagner, 1972). This is because, in a cue interference design, the interfering and interfered-with cues are not presented together on the same trial followed by the US. Therefore, no contest for entering into an association with the US should occur. More generally, the mechanisms widely used to account for cue competition cannot readily be applied to associative interference. Thus, reports suggesting parallel mechanisms underlying cue competition and cue interference challenge these accounts.

Amundson, Escobar, and Miller (2003, Experiment 1) obtained retrospective revaluation after proactive cue interference as a result of associative deflation of the first learned cue-outcome association after the target cue-outcome association was formed in Phase 2 (i.e., A-O followed by X-O, then A-). More specifically, using a first-order conditioning preparation, Amundson et al. trained three groups of rats that received target X-US pairings in Phase 2. Two interference groups received prior A-US pairings in Phase 1, while a control group received unpaired presentations of A and the US. During Phase 3, one of the two interference groups and the control group received nonreinforced presentations of A, while the other interference group received nonreinforced presentations of an irrelevant cue (B). More proactive interference was observed in rats that received nonreinforced exposure to the irrelevant cue B than in rats that received nonreinforced exposure of the interfering cue A. Amundson et al.'s results demonstrate retrospective revaluation of proactive cue interference, which suggests that the principles governing Cell 1 may also apply to Cell 3. However, more research is needed to further evaluate this proposition. To date, the possibility of retrospective revaluation of retroactive cue interference has not been examined.

EXPERIMENT 1

Experiment 1 sought evidence of retrospective revaluation of a target CS as a result of nonreinforced presentations of a retroactively interfering stimulus. It consisted of a four-

group study embedded in a sensory preconditioning situation (see Table 1). We used a sensory preconditioning design because retroactive cue interference is greatly attenuated if the outcome used during the interference phases of treatment is of high biological significance (Escobar, Matute, et al., 2001). Presumably the reduced sensitivity of first-order associations to interference reflects a functional resistance of biologically significant associations to various sources of degradation including associative interference (see Escobar, Matute, et al. for a discussion). However, when an interference design is embedded within a sensory preconditioning procedure, the two phases of interference occur before the biologically significant US is introduced (see Table 1). A 2 (Training: Interfering cue paired or unpaired with the outcome) $\times$ 2 (Revaluation: interfering cue associatively deflated or not deflated) design was used. Group Paired-Deflation was analogous to a retrospective revaluation group that receives nonreinforced presentations of the competing cue following cue competition treatment. Group Paired-Control controlled for the presentation of a stimulus after receiving retroactive interference treatment. Groups Unpaired-Deflation and Unpaired-Control controlled for interference. All groups were exposed to the same number of cues and US presentations, as well as equivalent context exposure. Expectations (see right column of Table 1) were based on the occurrence of retrospective revaluation of retroactive cue interference. Specifically, strong behavioral control by X was anticipated in Condition Unpaired (Groups Unpaired-Control and Unpaired-Deflation) given that no interference was expected to occur. Weak behavioral control by X, indicative of interference, was expected to occur in the Group Paired-Control due to a strong A-O association. In contrast, interference was not expected to occur in Group Paired-Deflation because, prior to testing, the interfering cue was presented without the reinforcer, which presumably reduced the effective strength of the interfering association.

Method

Subjects—The subjects were 24 male and 24 female, experimentally naive, Sprague-Dawley descended rats obtained from our own breeding colony. Body weight ranges were 169–226 g for males and 191–273 g for females. Subjects were randomly assigned to one of four groups ($n = 12$), counterbalanced within groups for sex. The animals were individually housed in standard hanging stainless steel wire mesh cages in a vivarium maintained on a 16/8 hr light/dark cycle. Experimental manipulations occurred near the middle portion of the light phase. The animals received free access to Purina Lab Chow, whereas water availability was limited to 20 min per day following a progressive deprivation schedule initiated one week prior to the start of the study. From the time of weaning until the start of the study, all animals were handled for 30-s, three times per week.

Apparatus—Six identical copies of Chamber V and of Chamber R were used. Chamber V was a 27-cm long box in a truncated-V shape (29.5-cm height, 21.5-cm wide at top, and 5.5-cm wide at bottom). The floor was comprised of two 27-cm long, 2-cm wide stainless steel plates, with a 1.5-cm gap between the two plates. The ceiling was clear Plexiglas, the front and back walls were black Plexiglas, and the sidewalls were stainless steel. A 0.7-mA, 0.5-s constant-current footshock, produced by a high voltage AC circuit in series with a 1.0-M Ω resistor, could be delivered through the metal walls and floor of the chamber. Each of six copies of Chamber V was housed in a separate sound- and light-attenuating environmental isolation chest. The chamber was illuminated by a 7-W (nominal at 120 VAC, but driven at 50 VAC) light bulb, which was mounted on the inside wall of the environmental enclosure, approximately 30-cm from the center of the experimental chamber. The light entered the chamber primarily by reflection from the ceiling of the environmental chest.

Chamber R was rectangular, measuring 24.0 $\times$ 9.0 $\times$ 12.5 cm (l $\times$ w $\times$ h). The walls and ceiling of Chamber R were clear Plexiglas, and the floor was comprised of stainless steel

rods measuring 0.5-cm diameter, spaced 1.3-cm apart (center to center). The rods were connected by NE-2 bulbs, which allowed for the delivery of a 0.7-mA, 0.5-s constant-current footshock. Each of six copies of Chamber R was housed in a separate light- and sound-attenuating environmental isolation chamber. Each chamber was dimly illuminated by a 2-W (nominal at 120 VAC, but driven at 50 VAC) incandescent house light mounted on an inside wall of the environmental chest located approximately 30 cm from the animal enclosure.

Chambers R and V could be equipped with a water-filled lick tube that extended 1-cm into a cylindrical niche, which was 4.5 cm in diameter, left right centered, with its bottom 1.75-cm above the floor of the apparatus and 5.0 cm deep. There was a photobeam detector 1-cm in front of the lick tube that was broken whenever the subject licked the tube.

Three 45- Ω speakers on the inside walls of each isolation chest could deliver a click train (6 Hz), a complex tone (500 Hz + 520 Hz), and a white noise. A buzzer could provide an additional auditory cue. All four auditory cues were 6dB above background as measured on the C-scale. A ventilation fan in each enclosure provided a constant 76-dB background noise. The light intensities inside the two illuminated chambers were approximately equal due to the difference in opaqueness of the walls of Chambers V and R.

CS X was always the click train. CSs A and B were the complex tone and the buzzer, counterbalanced within groups. The outcome (O) was always the white noise. Stimuli X, A, B and O were all 5 s in duration. The footshock served as the US. Context for each rat was held constant across the entire experiment. Two contexts rather than a single context were used based on equipment availability. The two contexts were counterbalanced within each group.

Procedure

Acclimation—On Days 1 and 2, all subjects were acclimated to drinking in their training context during a daily 30-min session. During the acclimation phase, subjects had free access to the water-filled lick tube. There were no presentations of any nominal stimuli during this phase. At the end of acclimation, the water tubes were removed until reacclimation.

Phase 1—On Day 3, all subjects were presented with 4 X-O trials (i.e., click-white noise) starting at 12, 24, 36 and 48 min into a 60-min session. On each of these trials, the onset of the outcome immediately followed the termination of X.

Phase 2—On Day 4, subjects in Condition Paired received 4 A-O presentations, starting at 12, 24, 36 and 48 min into a 60-min session. On each of these trials, the onset of the outcome immediately followed the termination of A. Subjects in Condition Unpaired received 4 unpaired presentations each of A and O. Presentations of A occurred at 7.0, 13.5, 33.5, and 47.0 min, while presentations of O occurred at 20.0, 27.1, 40.0 and 53.5 min into a 60-min session.

Phase 3—On Day 5, 6 and 7, subjects in Condition Control received 12 daily presentations of cue B alone, whereas subjects in Condition Deflation received 12 daily presentations of cue A alone. Presentations of cues occurred at 9.2, 18.4, 27.6, 36.9, 46.1, 55.3, 64.5, 73.7, 82.9, 92.2, 101.4, and 110.6 min into a 120-min session.

Phase 4—On Day 8, all subjects received 4 O-US trials starting at 12, 24, 36 and 48 min into a 60-min session. On each of these trials, O and the US co-terminated.

Reacclimation—On Days 9, 10, and 11, all subjects were reacclimated to reestablish stable drinking behavior (which might have been differentially disrupted by the footshock US) in two daily 30-min sessions. Sessions were separated by an interval of two hours. Subjects had free access to the water-filled lick tube, and no nominal stimuli were programmed to occur.

Test—On Day 12, all subjects were tested for conditioned lick suppression to CS X. Upon placement in the test chamber, time spent drinking by each subject was recorded. Immediately after completion of an initial five cumulative seconds of licking in the absence of any nominal stimulus, subjects were presented with CS X. Thus, all subjects were drinking at the time of CS onset. Time to complete an additional five cumulative seconds of licking in the presence of CS X was recorded. The times recorded during the presentation of CS X were interpreted as reflecting subjects' expectancy of the US following onset of the CS. The test session was terminated after the animals drank 5 cumulative seconds during the CS X presence. A ceiling score of 10 min was imposed on the time to complete five cumulative seconds of drinking in the presence of CS X. Thus, maximum test session duration was 11 minutes.

Results and Discussion

Experiment 1 results are summarized in Figure 2. Retroactive cue interference of the target X-O association was observed when a second association was formed with a different cue but the same outcome (A-O). Critically, the interference effect was reduced when the A-O association was associatively deflated by nonreinforced presentations of the interfering cue (i.e., extinction of CS A) during Phase 3. The observed recovery in responding to X when the interfering cue A was extinguished resembles the retrospective revaluation phenomena observed in cue competition situations when the associative status of the competing cue is deflated prior to test (e.g., Blaisdell et al., 1999; Cole et al., 1995; Kaufman & Bolles, 1981; Liljeholm & Balleine, 2006, 2009; Matzel et al., 1985; Shevill & Hall, 2004). The following statistics support these assertions.

A factorial analyses of variance (ANOVA), with factors of Phase 2 treatment (Paired vs. Unpaired) and Phase 3 treatment (Deflation vs. Control) performed on the data recorded prior to the test presentation of CS X (i.e., baseline drinking) revealed no significant differences, all $ps > .77$. An analogous ANOVA performed on the data recorded during CS X revealed a significance interaction, $F(1, 44) = 9.41, p < .01$, Cohen's $f = 0.44$ (95% CI = 0.15; 0.73), $MSE = .17$. Planned comparisons using the error term from the ANOVA were conducted to find the source of the interaction and to test specific hypotheses. Subjects in Group Paired-Control exhibited lower responding than subjects in Group Unpaired-Control, $F(1, 44) = 26.43, p < .01$, Cohen's $f = 0.74$ (95% CI = 0.41; 1.06), indicating that the reduced behavioral control by CS X in Group Paired-Control was due to the A-O association formed during Phase 2 (i.e., retroactive cue interference). Additionally, subjects in Group Paired-Control showed lower conditioned suppression than subjects in Group Paired-Deflation, $F(1, 44) = 22.46, p < .01$, Cohen's $f = 0.68$ (95% CI = 0.36; 0.99), which indicates that interference with the X-O association by the A-O association was disrupted when the interfering association A-O was associatively deflated (i.e., extinguished). Thus, this experiment documents retrospective revaluation by associative deflation of the competing cue in a retroactive cue interference situation. Nonreinforced presentations of the interfering cue presumably deflated its associative status, and consequently its potential to be retrieved and interfere with the target association.

EXPERIMENT 2

As previously stated, retrospective revaluation refers to changes in responding to a target cue as a result of changes in the associative status of a nontarget cue. Such changes in the associative status of the nontarget cue can take the form of either deflation or inflation. Experiment 1 found that providing nonreinforced presentations of the interfering cue (i.e., associative deflation) between retroactive interference training and the test reduced retroactive cue interference, a result that is analogous to retrospective revaluation after cue competition. The effect observed in Experiment 1 suggests that retroactive cue interference depends on the associative status of the interfering cue at the time of test. Complementing Experiment 1 in which the interfering A-O association was deflated, Experiment 2 further assessed the relationship between observed retroactive interference and the associative status of the interfering cue at test by inflating the interfering A-O association. Because, in a retroactive interference design, the interfering training trials follow the target training trials, inflation of the interfering A-O association amounts to simply administering additional Phase 2 trials. Thus, Experiment 2 varied the number of interfering A-O pairings with the expectation that more pairing would result in greater interference. Miller and Laborda (2011), among others, proposed that associative outcome interference is determined, at least in part, by the associative strength of each of the two interacting associations at the time of testing. Experiment 1 provided evidence that this principle also applies to cue interference. There we saw that reducing the strength of the competing association (A-O) prior to test reduced the observed interference. In Experiment 2, we reversed this strategy and asked whether increasing the strength of the interfering association through administration of more A-O pairings would increase the observed interference.

Specifically, Experiment 2 consisted of a five-group parametric study embedded in a sensory preconditioning paradigm, as was Experiment 1 (see Table 2). Group Int 0 received no A-O pairings, just like Condition Unpaired in Experiment 1. This group served as a control group to assess behavioral control with no associative interference. Groups Int 2, Int 3, Int 4, and Int 12 were analogous to Group Paired Control of Experiment 1, with the numbers in their names indicating the number of A-O pairings in Phase 2. These groups were expected to exhibit retroactive cue interference in varying degrees directly related to the amount of interfering training they experienced. All five groups were exposed to the same numbers of cues and outcome presentations, and context exposure was equated across groups. Expectations based on interference being dependent on the associative strength of the interfering cue are indicated in the right column of Table 2. We expected to observe more interference in groups that received higher numbers of A-O interference trials in Phase 2 (e.g., Group Int 12). Having a larger number of reinforced trials in Phase 2 is analogous to providing extra training (i.e., associative inflation) to the non-target cue after target training, which in cue competition can produce higher competition (i.e., a decrease in responding to the target cue; Balleine, Espinet, & Gonzalez, 2005; Denniston et al., 1996; Luque, Morís, Orgaz, Cobos, Matute, 2011; Miller & Matute, 1996; Vadillo, Castro, Matute, & Wasserman, 2008).

Method

Subjects—The subjects were 30 male and 30 female, experimentally naive, Sprague-Dawley-descended rats obtained from our own breeding colony. Body weight ranges were 205–305 g for females and 280–369 g for males. Subjects were randomly assigned to one of five groups ($n_s = 12$), counterbalanced within groups for sex. The maintenance and housing of subjects were the same as in Experiment 1.

Apparatus—The apparatus used were the same as in Experiment 1. CSs X was the click train. CSs A and B were the complex tone and the buzzer, counterbalanced within groups. The outcome (O) was the white noise. X, A, B, and O were 5 s in duration and 6 dB above background noise. The 0.5-s, 0.7-mA footshock served as the US. Context was held constant for each subject across the entire experiment, with the R and V chambers counterbalanced within groups.

Procedure

Acclimation and Phase 1—On Days 1 and 2, acclimation occurred as described in Experiment 1. On Day 3, all subjects received X-O training as described in Experiment 1.

Phase 2—On Days 4 and 5, all subjects received training in daily 90-min sessions. Subjects in Group Int 12 received 6 daily A-O pairings (starting at 13, 26, 33, 52, 65, and 78 min into the session). On each of these trials, the onset of the outcome immediately followed the termination of A. Subjects in Group Int 4 received 2 daily A-O pairings (starting at 26 and 65 min into the session) as well as 4 daily unpaired O presentations (starting at 13, 33, 52, and 78 min into the session) and 4 daily unpaired B presentations (starting at 39, 46, 58, and 71 min in the session). On Day 4, subjects in Group Int 3 received 2 A-O pairings (starting at 26 and 65 min) as well as 4 unpaired O presentations (starting at 13, 33, 52, and 78 min) and 4 unpaired B presentations (starting at 39, 46, 58, and 71 min). Additionally, on Day 5, subjects in Group Int 3 received 1 A-O pairing (starting at 26 min) as well as 5 unpaired O presentations (starting at 13, 33, 52, 65, and 78 min) and 5 unpaired B presentations (starting at 19, 39, 46, 58, and 71 min). Subjects in Group Int 2 received 1 daily A-O pairing (starting at 26 min) as well as 5 daily unpaired O presentations (starting at 13, 33, 52, 65, and 78 min) and 5 unpaired B presentations (starting at 19, 39, 46, 58, and 71 min). Subjects in Group Int O received no A-O pairings, 6 daily unpaired O presentations (starting at 13, 26, 33, 52, 65, and 78 min), and 6 unpaired B presentations (starting at 6, 19, 39, 46, 58, and 71 min).

Phase 3, Reacclimation, and Test—On Day 6, all subjects received 4 O-US pairings as in Phase 4 of Experiment 1. On Days 7–9, reacclimation took place, and on Day 10 testing occurred as described in Experiment 1.

Results and Discussion

The results of Experiment 2 are summarized in Figure 3. Retroactive cue interference with expression of the X-O association was observed when a second association was formed with a different cue but the same outcome (A-O). Critically, the magnitude of the interference effect was a direct function of the number of interfering A-O pairings administered in Phase 2. The observation of decreased responding to X when the interfering cue A was further reinforced resembles retrospective revaluation phenomena reported in cue competition when the associative status of the competing cue is inflated prior to test (i.e., backward blocking; e.g., Denniston et al., 1996; Miller & Matute, 1996; Shanks, 1985). The following statistics support these assertions.

A one-way ANOVA performed on the data recorded prior to the test presentation of CS X (i.e., baseline drinking) revealed no significant differences across groups, $F(4, 55) = 0.64$, $p = .63$. An analogous ANOVA performed on the data during CS X revealed an effect of number of interference trials, $F(4, 55) = 35.22$, $p < .01$, Cohen's $f = 1.51$ (95% CI = 1.13; 1.90), $MSE = .08$. Planned comparisons using the error term from the ANOVA were conducted to test specific hypotheses. Group Int 2 showed significantly lower conditioned suppression relative to Group Int 0, $F(1, 55) = 6.35$, $p < .01$, Cohen's $f = 0.32$ (95% CI = 0.06; 0.58). This difference was expected because in Group Int 2 an interfering association

(A-O) was formed in Phase 2, which presumably did not exist in Group Int 0. Therefore, the retrieval of the X-O association was subject to retroactive interference at test, resulting in lower suppression to X relative to when a second association with the outcome is absent (as in Group Int 0). Responding in Group Int 3 was also lower than responding in Group Int 0, $F(1, 55) = 17.65, p < .01$, Cohen's $f = 0.54$ (95% CI = 0.13; 0.81), although the three A-O trials given to Group Int 3 only provoked a marginal decrease in responding relative to 2 interfering trials (i.e., Group Int 2), $F(1, 55) = 2.82, p = .09$, Cohen's $f = 0.21$ (95% CI = 0.00; 0.47). Greater differences were observed when 4 (i.e., Group Int 4) rather than 3 (i.e., Group Int 3) interfering trials were administered, $F(1, 55) = 17.89, p < .01$, Cohen's $f = 0.54$ (95% CI = 0.27; 0.82). Finally, marginally greater interference was observed with 12 (i.e., Group Int 12) rather than 4 (i.e., Group Int 4) interference trials, $F(1, 55) = 3.08, p = .08$, Cohen's $f = 0.22$ (95% CI = 0.00; 0.48). This was probably due to approximation to floor levels of suppression after four trials. Overall, the level of responding to X at test was negatively correlated with the number of interfering trials given during Phase 2, Pearson's $r(58) = -.73, p < .01$. Thus, this experiment documents retrospective revaluation of retroactive cue interference when retrospective revaluation is achieved through associative inflation of the interfering cue.

GENERAL DISCUSSION

This series of experiments further demonstrates that different cues trained in sequential phases with the same outcome can interfere with behavioral control by each cue (e.g., Amundson et al., 2003; Escobar, Matute, et al., 2001; Matute & Pineño, 1998a, 1998b; Miguez, Cham, et al., 2012). Here we saw that the nontarget A-O association learned during Phase 2 retroactively interfered with behavioral expression of the target X-O association acquired during Phase 1. The experiments were embedded within a sensory preconditioning procedure because associative retroactive cue interference is appreciably attenuated if the target CS acquires high biological significance before the interference treatment as would be the case during first-order conditioning (Escobar, Matute, et al., 2001). In Experiment 1, retroactive cue interference was demonstrated in a sensory preconditioning paradigm. After X-O pairing in Phase 1, subjects exhibited low responding to the target cue X, when a second cue, A, was associated with the same outcome in Phase 2 (Group Paired-Control), but not when unpaired presentations of A and the outcome were provided in Phase 2 (Condition Unpaired). That is, it was not merely degradation of the target-outcome contingency as a result of exposure to the outcome in Phase 2 that produced a decrement in conditioned suppression, but the existence of an interfering association. Furthermore, when the A-O association was presumably extinguished by nonreinforced presentations of A in Phase 3 (Group Paired-Deflation), behavioral control by X increased, suggesting improved retrieval of the X-O association. That is, subjects suppressed more when the associative status of the interfering cue was reduced. Thus, the retroactive cue interference observed in Group Paired-Control seemingly was due to a failure to retrieve the X-O association at test rather than any unlearning of the X-O association during Phase 2. Notably, reduction of the A-O association was produced by extinction (i.e., A-no outcome), itself a form of associative outcome interference.

Our results suggest that retrospective revaluation occurs in retroactive cue interference, just as it occurs in proactive cue interference (Amundson et al., 2003), and is analogous with similar reports of retrospective revaluation in cue competition (Cell 1 of Figure 1) and outcome competition (Cell 2 of Figure 1). For example, posttraining extinction of an overshadowing or blocking cue sometimes produces an increase in responding to the overshadowed cue (Kaufman & Bolles, 1981; Liljeholm & Belleine, 2006; 2009; Matzel et al., 1985; Shevill & Hall, 2004) or blocked cue (Blaisdell et al., 1999). Similarly, Burger, Mallema, and Miller (2000) reported that posttraining extinction of an overshadowing

outcome (i.e., X-[O1+O2] pairings followed by presentations of O2 alone) resulted in recovery of responding based on the X-O1 association. A highly similar finding has also been observed in blocking of outcomes (i.e., X-O2 pairings prior to X-[O1+O2] pairings, followed by presentations of O2 alone which increased responding based on the X-O1 association; Wheeler & Miller, 2005). In conjunction with Amundson et al.'s results, our data suggest that degrading the interfering association in cue interference (Cell 3 of Figure 1) enhances behavioral control by the target cue. More broadly, this observation parallels other reports concerning Cells 3 and 4 which suggest that, in associative interference, responding to the target CS depends on how readily the interfered-with association is retrieved at test in comparison with the retrieval of the interfering association, which has been manipulated by varying the similarity of the test context with the contexts of Phase 1 and Phase 2 training (Amundson et al.; Bouton & Bolles, 1979; Escobar, Arcediano, et al., 2001; Escobar, Matute, et al., 2001; González-Martín, Cobos, Morís, & López, 2012; Miguez, Cham, et al., 2012; Miguez, Witnauer, Laborda, & Miller, in press; Rosas, García-Gutiérrez, & Callejas-Aguilera, 2006; Rosas, Vila, Lugo, & López, 2001).

In Experiment 2, we further replicated the observation of retroactive cue interference within a sensory preconditioning procedure. In general, subjects exhibited lower levels of behavioral control by target cue X in direct relationship to the strength of the interfering A-O association, which was manipulated through the number of A-O pairings. As in Experiment 1, decreased behavioral control by X was not merely due to degradation of the target cue-outcome contingency produced by exposure to the outcome during Phase 2. This was evident in that all groups received the same number of exposures to O in Phase 2 as a result of our administering increasing numbers of unsignaled Os as the number of A-O pairings decreased. Notably, these unsignaled exposures to O controls for the degradation of the contingency of X with O across phases. But it may have additionally produced differential degradation of the contingency of the A with O during Phase 2, with greater degradation in those circumstances that the A-O association received few training trials, which may have added to weaken the effective A-O association. However, we speculate that the relatively long intertrial intervals used in Phase 2 likely minimized the role of degraded contingency produced by presentations of O alone as degraded contingency effects are known to decrease when long intertrial intervals facilitate extinction of context-outcome associations. In sum, with our parameters, reduction in behavioral control by X was positively related to the amount of training of the interfering A-O association and possibly inversely related to the number of unsignaled O presentations. Presumably, the associative status of the interfering association was greater with more A-O trials. The observed decrease in behavioral control by X when the interfering cue A was further reinforced parallels retrospective revaluation phenomena often reported in cue competition when there is additional reinforcement of the competing cue by itself (e.g., Balleine et al., 2005; Denniston et al., 1996; Luque et al., 2011; Miller & Matute, 1996; Vadillo et al., 2008).

In the present research we have focused on Cell 3 of Figure 1, which includes retroactive and proactive interference between cues trained in different phases with a common outcome. Other reports have assessed the possibility that the mechanisms underlying Cell 3-type interference may be similar to those of Cell 4, which consists of interference between outcomes (e.g., Amundson et al., 2003; Escobar, Arcediano, et al., 2001; Escobar, Matute, et al., 2001; Luque, Morís, & Cobos, 2010; Miguez, Cham, et al., 2012). Notably, Cell 3 and Cell 1 phenomena both encompass a common outcome. Because phenomena in these two cells involve reduction in behavioral control by cues trained with a common outcome, one might expect analogous underlying mechanisms.

The present findings, together with previous reports of analogies between Cell 1 and Cell 3 of the matrix presented in Figure 1, suggest that the mechanisms governing the decrement in

behavioral control that is observed when an interfering or competing association is formed (or strengthened as in Experiment 2), as well as the mechanisms involved in the recovery from interference or competition when the interacting association is weakened or rendered less effective (as in Experiment 1), have more in common than originally thought. Furthermore, in conjunction with reports that compare other cells of the matrix (e.g., Amundson et al., 2003; Burger et al., 2000; Escobar, Arcediano, et al., 2001; Escobar, Matute, et al., 2001; Esmoris-Arranz et al., 1997; Lipatova, Wheeler, Vadillo, & Miller, 2006; Luque et al., 2010; Matute, Arcediano, & Miller, 1996; Miguez, Cham, et al., 2012; Wheeler & Miller, 2005), the growing body of research seems to strongly suggest that at least some principles span across all four types of stimuli interactions depicted in Figure 1.

Most associative models (e.g., Mackintosh, 1975; Miller & Matzel, 1988; Pearce, 1987; Pearce & Hall, 1980; Rescorla & Wagner, 1972; Wagner, 1981) can readily explain the phenomena in Cell 1. This is not surprising given these models were created with the purpose of accounting for competition between cues when they are trained together (Cell 1 of Figure 1). These models account for the observed reduction in responding produced by cue competition either as a failure to acquire an association with the outcome (e.g., Pearce, 1987; Pearce & Hall, 1980; Rescorla & Wagner, 1972) or a failure to activate the representation of the outcome at test (e.g., Miller & Matzel, 1988; also see Stout & Miller, 2007). Nevertheless, only the Miller and Matzel (1988) model can adequately account for competition between outcomes (Cell 2), in addition to competition between cues (see Miller & Escobar, 2002). Less numerous are models that are able to account for associative interference. Bouton's (1993) model of retrieval interference was designed to account for interference between outcomes trained apart (Cell 4). More recently, accounts of interference between cues (Cell 3) have been proposed. Miller and Escobar (2002) presented a modification of Bouton's (1993) model that anticipates parallel effects between outcome and cue interference (Cells 3 and 4). Specifically, the Miller and Escobar model poses two mechanisms that work simultaneously. The first mechanism is a comparator process through which responding to a target cue is directly mediated by the target CS-outcome association and indirectly mediated by both the association of the target CS with other stimulus that were present during training and the association between these other stimuli and the outcome. The second mechanism is a priming process in which priming of the target association at test increases responding while actively decreasing the retrieval of other associations that share a common element, and vice versa. The model stresses that the first mechanism is predominant in Cells 1 and 2 of the matrix because in those cells the two competing associations are equally primed at test due to their having been trained together (i.e., in the same context), thereby neutralizing the second mechanism. In contrast, the second mechanism is presumably predominant in Cells 3 and 4 because there are no within-compound associations and consequently a comparator process is prevented. Notably, Miller and Escobar's accounts of stimulus interaction in Cell 1 and Cell 3, which posit different underlying mechanisms for the two cells, seem difficult to reconcile with the observations of the present experiments.

Some of the models that account for competition between cues (i.e., Cell 1) have been modified to account for retrospective reevaluation in cue competition (e.g., Dickinson & Burke, 1996; Van Hamme & Wasserman, 1994). These models purpose that the associative status of an absent but expected cue should decrease on a trial if the outcome is present and increase if the outcome is absent. This account may also be applied to some retroactive cue interference preparations that do not control for the presentation of the outcome (e.g. Luque, Morís, Orgaz, Cobos, & Lopez, 2009; Ortega & Matute, 2000). Here (without unsignaled Os in Phase 2), during an A-O presentation the O might evoke an expectation of X (based on the X-O association from Phase 1), thereby decreasing the associative status of X according to these models. However, in our retroactive cue interference design, presentations of the

outcome were equivalent in number across conditions; therefore, expectation of cue X on each presentation of O in Phase 2 (with or without A) should have been the same across groups, and consequently should have produced equal interference in all groups, which was not observed. Therefore, the Van Hamme and Wasserman and Dickinson and Burke models fail to predict our basic retroactive cue interference effect. Furthermore, these two models fail to anticipate the retrospective revaluation that we observed when A was associatively deflated (i.e., extinguished) during Phase 3 in Experiment 1. Cue A had no association with X; consequently presentation of A alone in Phase 3 should not have activated the representation of X, with the result that there should have been no change in the response potential of X. This is of course contrary to what we observed.

The observed dependence of interference on A-O pairings rather than mere presentations of O lend support to Miller and Escobar's (2002) account that posits that it is the interfering association, rather than a decrease in X's contingency, that drives interference. Several other reports (e.g., Amundson et al., 2003; Escobar, Matute et al., 2001; Miguez et al., 2011) that have used control conditions similar to ours converge in supporting the perspective that interference occurs between associations. Additionally, Vadillo, Orgaz, and Matute (2008) provided evidence supportive of this view when they observed less interferences when the interfering association was overshadowed.

The finding of retrospective revaluation in cue interference analogous to retrospective revaluation in cue competition suggests the existence of a common underlying mechanism for both types of stimulus interaction. Thus, the present results add to an emerging literature highlighting the similarity between the reductions in associatively driven behavior produced by cue competition (i.e., when cues are trained together) and cue interference (i.e., when cues are trained apart).

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	Interacting Events	
	Antecedent Events	Subsequent Events
Trained Together (Competition)	<p>Cue competition (e.g., overshadowing, relative validity, overexpectation)</p> <p>Cell 1</p>	<p>Outcome competition (e.g., Rescorla, 1980; Esmoriz-Arrans, Matute, & Miller, 1997; Miller & Matute, 1998)</p> <p>Cell 2</p>
Trained Apart (Interference)	<p>Retroactive cue interference, proactive cue interference (e.g., Escobar, Matute, & Miller, 2001; Miguez, Cham, et al., 2012; Amundson et al., 2003)</p> <p>Cell 3</p>	<p>Retroactive outcome interference, proactive outcome interference (e.g., extinction, latent inhibition, counterconditioning)</p> <p>Cell 4</p>

Figure 1.

A 2×2 matrix of different types of associative interference and competition, all of which produce a decrease in control of behavior by the target stimulus (X). In each cell some representative examples are listed (after Miller & Escobar, 2002). O1 and O2 are outcomes of opposite valence; X and A are cues. See text for discussion.

Figure 2.

Results of Experiment 1. Mean times to complete 5 cumulative s of drinking in the presence of the target CS X. Higher scores represent stronger responding to the test CS. Error bars represent standard error of the mean. 0.70 = no suppression. See text and Table 1 for details.

Figure 3.

Results of Experiment 2. Mean times to complete 5 cumulative s of drinking in the presence of the target CS X. Higher scores represent stronger responding to the test CS. Error bars represent standard error of the mean. 0.70 = no suppression. See text and Table 2 for details.

Table 1

Design of Experiment 1

Group	Phase 1	Phase 2	Phase 3	Phase 4	Test	Expected
Paired-Control	4 X-O	4 A-O	36 B-	4 O+	X	cr
Paired-Deflation	4 X-O	4 A-O	36 A-	4 O+	X	CR
Unpaired-Control	4 X-O	4 A/O	36 B-	4 O+	X	CR
Unpaired-Deflation	4 X-O	4 A/O	36 A-	4 O+	X	CR

Note: X was a click. A and B were a complex tone and a buzzer, counterbalanced. O was a white noise. + denotes a brief footshock US. Numbers before letter represent total number of presentations in that phase. Expectations are based on retrospective reevaluation of retroactive cue interference, with capital letters representing greater behavioral control by CS X.

Table 2

Design of Experiment 2

Group	Phase 1	Phase 2-----	Phase 3	Test	Expected
Int 0	4 X-O	12 O/12 B	4 O+	X	CR
Int 2	4 X-O	2 A-O/10 O/10 B	4 O+	X	Cr
Int 3	4 X-O	3 A-O/9 O/9 B	4 O+	X	Cr
Int 4	4 X-O	4 A-O/8 O/8 B	4 O+	X	cr
Int 12	4 X-O	12 A-O	4 O+	X	-

Note: X was a click. A and B were a complex tone and a buzzer, counterbalanced. O was a white noise. + denotes a brief footshock US. Numbers before letter represent total number of presentations in that phase. Expectations are based on retrospective reevaluation of retroactive cue interference, with capital letters representing greater behavioral control by CS X.