Journal of Experimental Psychology:
Human Perception and Performance
2015, Vol. 41, No. 6, 1475–1481

0096-1523/15/$12.00 http://dx.doi.org/10.1037/xhp0000122

OBSERVATION

Adapting to Stimulus–Response Contingencies Without Noticing Them

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Episodic stimulus–response (S–R) bindings emerge whenever a response is executed in temporal proximity to a stimulus and they are retrieved from memory by repeating the stimulus on a later occasion. To examine whether retrieval of S–R bindings is sensitive to contextual influences, we manipulated contingencies between stimulus repetitions and response repetitions. In a sequential priming paradigm, stimulus repetitions were either predictive of response repetitions (positive contingency) or response changes (negative contingency) or were orthogonal to the response relation (no contingency). Results revealed that compared to the orthogonal condition, S–R binding and retrieval effects were larger under positive contingency but were reduced under negative contingency. The modulating effect of contingency on the strength of S–R binding and retrieval processes was not mediated by contingency awareness. These findings implicate that S–R binding and retrieval processes are implicitly tuned to adapt to contextual affordances that either promote or hinder the use of S–R bindings for efficient action regulation.

Keywords: stimulus–response binding, event files, episodic retrieval, contingency awareness, implicit learning

Whenever a response is executed to a stimulus, their mental codes become integrated into a transient episodic memory structure called stimulus–response (S–R) binding or "event file" (Hommel, 1998). Repeating the stimulus later on triggers retrieval of the associated response, which either facilitates or hampers performance, depending on whether the retrieved response is appropriate or not in the novel situation. S–R binding and retrieval processes play an important role for an efficient, stimulus-based control of behavior (Logan, 1988; Rothermund, Wentura, & De Houwer, 2005). To date, a burgeoning amount of evidence documents that binding and retrieval are pervasive principles of action regulation and apply to a broad scope of stimuli (Denkinger & Koutstaal, 2009; Frings, Rothermund, & Wentura, 2007; Giesen & Rothermund, 2011, 2014a; Hommel, 1998; Horner & Henson, 2011; Mayr & Buchner, 2006; Moeller, Rothermund, & Frings, 2012) and responses (Giesen & Rothermund, 2014b; Giesen, Herrmann, & Rothermund, 2014; Henson, Eckstein, Waszak, Frings, & Horner, 2014; Horner & Henson, 2009).

Most of the existing studies assume that S–R binding/retrieval occurs in an automatic fashion (Mayr & Buchner, 2010), because stimulus-based response retrieval is typically observed *irrespective* of whether the retrieved response is beneficial or not in a certain situation (i.e., in designs were stimulus relation and response relation are orthogonal). However, it was also demonstrated that processes of episodic retrieval are *context-sensitive* and can be experimentally induced by particular context manipulations (Frings & Wentura, 2008; Kane, May, Hasher, Rahhal, & Stoltzfus, 1997; Lowe, 1979). For instance, in contexts where episodic retrieval is beneficial (if stimulus repetitions are frequent), episodic retrieval processes are strengthened and participants will rely more on them, whereas the reverse is true for contexts in which episodic retrieval typically disrupts performance (Kane et al., 1997; Lowe, 1979).

Against this background, we were interested in whether effects of transient S–R binding and retrieval can be flexibly adapted to contextual affordances (i.e., to conditions in which reliance on S–R binding/retrieval is advantageous or detrimental for performance) or whether these processes operate in a rigid fashion that is independent of such contextual qualifications. Furthermore, we examined whether adaptive modulations of S–R binding and retrieval processes are mediated by participants' awareness of the contextual contingencies between stimulus and response repetitions, or whether such an adaptation occurs automatically, that is, independently of conscious insight into the contingencies.

In the present study, we asked participants to categorize the color of words via key press. Word stimuli and responses could either repeat or change from one trial to the next. By manipulating the contingencies between stimulus repetitions and response repetitions across blocks, we created contexts that either reinforced or punished relying on S–R binding/retrieval: Stimulus repetitions were either predictive of response repetitions (positive contin-

This article was published Online First September 21, 2015.

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This research was supported by a grant from the Deutsche Forschungsgemeinschaft to Klaus Rothermund (DFG RO1272/6-2).

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gency) or of response changes (negative contingency) in the majority of trials per block. Under a positive contingency, retrieval of previous response episodes activates responses that are typically correct, whereas under a negative contingency, retrieval activates a response that typically conflicts with the required response. We also included a neutral condition in which stimulus and response relation were varied orthogonally (no contingency) that should yield "standard" S–R binding/retrieval effects (indicated by a Stimulus Relation × Response Relation [S × R] interaction). If effects of S–R binding and retrieval flexibly adapt to contextual affordances, S–R retrieval effects should be amplified (reduced) in the positive (negative) contingency block, compared to the neutral block. However, if binding and retrieval processes operate irrespective of context influences, S–R retrieval effects should not differ between blocks (the three-way interaction should be absent). To assess participants' awareness of the contingency manipulation, we interspersed a number of *guessing trials* within each block to obtain indicators of subjective S–R contingency awareness.

Method

Participants

Sixty native German-speaking students of the University Jena were recruited for the experiment. One participant had to be excluded due to high error rates (>20%). Data of 59 (35 female) participants ($M_{\text{age}} = 22.3$ years; $SD = 2.8$) were analyzed. Participants were tested individually and received €2 for their participation plus an additional amount of up to €1, depending on their performance in the guessing trials. Sessions lasted 30 min.

Apparatus and Stimuli

The experiment was programmed with E-Prime 2.0. Stimuli were 25 neutral, frequent, mono-/disyllabic German adjectives that were presented in Times New Roman font (16 pt.) on a black 17-in. CRT screen. Participants responded by pressing "D" or "L."

Design

The experiment comprised three within-subject factors: stimulus relation, response relation, and block type. Stimulus relation was manipulated by repeating or changing the word from trial$_n$ to trial$_{n+1}$ (50% stimulus repetition; 50% baseline). Response relation was manipulated by requiring the same or a different response from trial$_n$ to trial$_{n+1}$ (50% response repetition; 50% response change). Block type was manipulated across three blocks: In the positive contingency block, stimulus repetitions co-occurred with response repetitions in 75% of trials, whereas the opposite proportion (25%) was realized for baseline trials (see Table 1). In the negative contingency block, stimulus repetitions co-occurred with response changes in 75% of trials (and vice versa for baseline trials). In the orthogonal block, stimulus relation and response relation were manipulated independently of each other. Stimulus color was counterbalanced in all blocks. Block order was counterbalanced across participants; because it did not interact with the

Table 1
Number (Percent) of Color Categorization Trials per Condition, Mean Probe RTs (SD) in ms, and Probe Error Rates for Every Condition of the Factorial Design as Well as Contingency Awareness Scores (Derived From Color Guessing Trials) per Block

Block type	Stimulus relation trial$_n$ → trial$_{n+1}$	# (%) of trials: Response relation trial$_n$ → trial$_{n+1}$		Probe RT: Response relation		% Probe errors: Response relation		Contingency awareness
		RR	RC	RR	RC	RR	RC	*M (SD)*
Positive contingency	Repetition (same word)	60 (75%)	20 (25%)	360 (43)	426 (49)	3.3 (3.2)	10.2 (11.5)	.60 (.11)
	Baseline (different word)	20 (25%)	60 (75%)	407 (51)	404 (50)	7.8 (7.8)	4.3 (4.6)	
	SRE			47*** [4]	−24*** [3]	4.5*** [.9]	−5.9*** [1.3]	
	S × R			71*** [6]		10.4*** [1.8]		
Negative contingency	Repetition (same word)	20 (25%)	60 (75%)	382 (47)	415 (47)	4.8 (6.4)	6.3 (6.1)	.55 (.09)
	Baseline (different word)	60 (75%)	20 (25%)	398 (49)	412 (50)	5.9 (6.0)	4.8 (6.7)	
	SRE			16*** [3]	−3 [3]	1.1 [.8]	−1.5 [.8]	
	S × R			19*** [4]		2.6 [1.3]		
Orthogonal	Repetition (same word)	40 (50%)	40 (50%)	375 (46)	420 (51)	3.4 (4.5)	6.1 (6.4)	.57 (.09)
	Baseline (different word)	40 (50%)	40 (50%)	398 (49)	411 (51)	5.9 (5.6)	5.0 (6.6)	
	SRE			23*** [2]	−9*** [2]	2.5*** [.6]	−1.1 [.9]	
	S × R			32*** [4]		3.6** [1.1]		

Note. RT = reaction time; RR = response repetition; RC = response change; SRE = stimulus repetition effect, computed as the difference of baseline minus repetition (SRE = B − R). S × R = Stimulus Relation × Response Relation interaction effects, computed as the difference of SRE for response repetition minus SRE for response changes (S × R = SRE$_{RR}$ − SRE$_{RC}$). Standard deviations in parentheses; standard errors of the mean in squared brackets.
* $p < .05$. ** $p < .01$. *** $p < .001$.

factors of interest, all analyses were performed with this factor collapsed.

Procedure

Instructions were given on screen. Participants were informed that in each trial, a word would appear centrally on screen in white font that would change its color to either red or green which they then had to categorize by pressing the green (D) or red (L) key. The meaning of the word was irrelevant for the task (Rothermund et al., 2005). On some trials, the word remained white and a question mark appeared above it. In such a *guessing trial*, the word from the preceding trial was either repeated or changed and participants were asked to guess in which color they expected the stimulus should have been printed by pressing the green or red key. Participants were told that each correct (wrong) guess would earn (cost) them +(–)5 cents and that at the end of the experiment, the extra money gained in the guessing task was added to their regular compensation. Incentivizing the guessing responses financially made sure that participants were motivated to show optimal guessing performance and to use any hunch or insight they might have with regard to S–R contingencies.

Each trial started with a fixation cross (500 ms) followed by a white word for a variable duration (250–400 ms). On color categorization trials, the word then changed its color to red/green until key press (maximum 1,500 ms), followed by the next trial. On guessing trials, a question mark appeared above the white word until participants gave their color guesses. Then, participants received feedback (2,000 ms): The word appeared in its "correct" color and participants were informed about their account's status and whether they had earned/lost money (the "correct" word color corresponded to the stimulus repetition/color repetition contingencies of the respective block). Each guessing trial was followed by a filler trial in which the values of the factors stimulus/response relation were freely chosen so that the next trial fulfilled the constraints of the experimental design. Filler trials were not analyzed. Within each block, trials were presented consecutively, meaning that each trial served simultaneously as a probe for the previous trial and as a prime for the subsequent trial.

Participants performed 44 practice trials with no contingency, followed by three experimental blocks (with positive, negative, and no contingencies, respectively), each consisting of 160 color categorization, 32 guessing, and 33 filler trials. Trials were presented randomly; guessing trials occurred pseudorandomly with an average of five trials in between. After the experiment, participants received a funneled debriefing to probe them for awareness of the contingency manipulation (see Table 2) and were rewarded for their participation.

Table 2
Funneled Debriefing Procedure, Forced-Choice Answers Provided by Participants, and Resulting Number of Participants Who Correctly Identified the Contingency Relation per Block

Question	Answer: Yes	Answer: No
1. Did you have the impression that the three experimental blocks differed from each other? (yes/no)	12	47
2. Did you have the impression that word repetitions often co-occurred with color repetitions or color changes in a given block? (yes/no)	35	24
	Correct identification of contingency[a]: Yes	No
3. Please judge the relationship of word repetitions and color repetitions in the *first* block: Repeated words . . .	18	41
a. . . . equally often repeated and changed their color.		
b. . . . more often co-occurred with color repetitions.		
c. . . . more often co-occurred with color changes.		
4. Please judge the relationship of word repetitions and color repetitions in the *second* block: Repeated words . . .	19	40
a. . . . equally often repeated and changed their color.		
b. . . . more often co-occurred with color repetitions.		
c. . . . more often co-occurred with color changes.		
5. Please judge the relationship of word repetitions and color repetitions in the *last* block: Repeated words . . .	22	37
a. . . . equally often repeated and changed their color.		
b. . . . more often co-occurred with color repetitions.		
c. . . . more often co-occurred with color changes.		
Summed number of blocks in which Word Relation × Response Relation contingency was correctly identified across Questions 3 to 5[b]	*n*	%
0	16	28.3
1	33	55.0
2	4	6.7
3	6	10.0

[a] Correct identification of contingencies in the first/second/last block was coded separately for each participant and depended on the respective block order condition. [b] Participants who correctly identified the contingencies within at least two blocks were categorized as being aware of the contingency manipulation.

Results

Probe Performance

Trials with erroneous responses in the prime and/or probe (10.1%) and reaction time (RT) outliers below 150 ms or above 775 ms (1.3%; Tukey, 1977) were discarded. Table 1 provides mean probe RTs and error rates.

Mean RTs were entered to a 2 × 2 × 3 repeated-measurement analysis of variance (ANOVA) with the factors stimulus relation, response relation, and block type, respectively. Only effects of theoretical interest are discussed (see Table 3 for global ANOVA results). As predicted, there was a significant S × R interaction, replicating typical S–R binding and retrieval effects (Rothermund et al., 2005): Compared to baseline, stimulus repetition produced a significant benefit of $\Delta = 29$ ms, $t(58) = 14.19$, $p < .001$, for response repetitions, but led to a significant cost of $\Delta = -11$ ms, $t(58) = 6.43$, $p < .001$, for response changes. Furthermore, the three-way interaction of block type, stimulus relation, and response relation was significant, indicating that effects of S–R binding/retrieval were sensitive to the contingency manipulation (Table 1; Figure 1a). Planned contrasts showed that compared to the neutral block, the S × R interaction was significantly stronger in the positive contingency block, $F(1, 58) = 41.89$, $p < .001$, $\eta_p^2 = .42$, but was significantly reduced in the negative contingency block, $F(1, 58) = 7.01$, $p = .01$, $\eta_p^2 = .11$. Error data revealed a highly similar pattern that replicated the RT findings (see Tables 1, 3; Figure 1b).

Contingency Awareness

To obtain comparable indicators of contingency awareness for the three blocks, color guesses were scored in accordance with an idealized positive contingency logic: For stimulus repetitions, "color repetition" guesses were counted as +1, whereas "color change" guesses were counted as 0. For baseline trials, the reverse

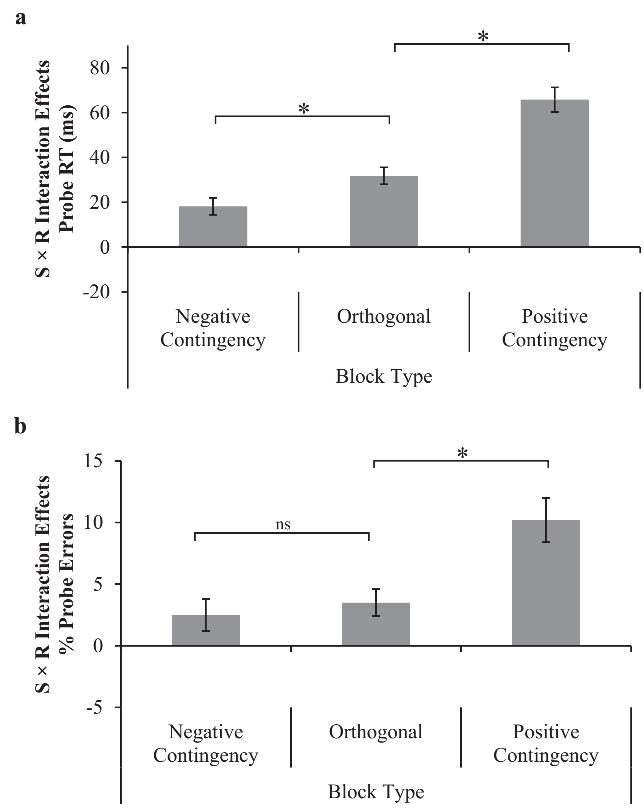

Figure 1. Stimulus Relation × Response Relation (S × R) interaction effects computed as the difference of stimulus repetition effects (SREs) for response repetition and response change sequences ($SRE_{RR} - SRE_{RC}$) as a function of block type for (a) mean probe reaction times (RTs) and (b) probe error rates. Positive interaction effects indicate stimulus-based retrieval of previous responses, reflected in facilitation effects (positive SRE) for response repetition sequences and/or interference effects (negative SRE) for response change sequences (see Table 1). Error bars depict standard errors of the means.

coding rationale was applied (color repetition guesses = 0, color change guesses = +1). Perfect awareness of each block's contingencies would lead to averaged scores of +1 and 0 for the positive and negative contingency blocks, respectively.

Averaged contingency awareness scores for the three blocks are shown in Table 1. Generally, contingency scores were close to .5, indicating low levels of contingency awareness. However, mean levels of contingency awareness differed significantly between blocks, $F(2, 57) = 5.64$, $p = .006$, $\eta_p^2 = .17$: Planned contrasts showed that compared to the neutral block, contingency scores were larger in the positive contingency block, $F(1, 58) = 6.24$, $p = .02$, $\eta_p^2 = .10$, but were nonsignificantly lower in the negative contingency block, $F(1, 58) = 1.23$, $p = .27$, $\eta_p^2 = .02$.

To test whether the block differences in S–R retrieval effects were mediated by differences in contingency awareness, we applied the regression method (Draine & Greenwald, 1998) and performed two regression analyses in which the two contrasts (positive vs. neutral, negative vs. neutral) in S–R binding/retrieval effects were predicted by the difference in contingency awareness between the respective blocks (see Table 4). None of these regres-

Table 3
Summary Table for ANOVA Results on Mean Probe RT and Mean Probe Error Rates

Variables	*df* 1	*df* 2	*F*	*p*	η_p^2
Probe RT					
Stimulus relation (S)	1	58	57.79***	.000	.49
Response relation (R)	1	58	133.32***	.000	.70
Block type (B)	2	57	.53	.59	.02
S × R	1	58	177.95***	.000	.75
S × B	2	57	2.41	.10	.08
R × B	2	57	2.99	.06	.10
S × R × B	2	57	32.86***	.000	.54
Probe errors					
S	1	58	.02	.99	.00
R	1	58	3.49	.07	.06
B	2	57	2.30	.11	.08
S × R	1	58	34.91***	.000	.38
S × B	2	57	2.06	.14	.07
R × B	2	57	1.07	.35	.04
S × R × B	2	57	7.59**	.001	.21

Note. ANOVA = analysis of variance; RT = reaction time; *df* = degrees of freedom.
* $p < .05$. ** $p < .01$. *** $p < .001$.

Table 4
Regression Analyses for Predicting Differences in Stimulus–Response Binding and Retrieval Effects by Differences in Subjective Contingency Awareness

Criterion	Variable	*B*	*SE B*	β
Contrast positive vs. neutral	Constant	32.95***	5.78	
($\Delta = S \times R_{positive} - S \times R_{orthogonal}$)	$\Delta = CA_{positive} - CA_{orthogonal}$	92.04	49.29	.24
Contrast negative vs. neutral	Constant	−14.48**	5.45	
($\Delta = S \times R_{negative} - S \times R_{orthogonal}$)	$\Delta = CA_{negative} - CA_{orthogonal}$	−16.79	42.38	−.05

Note. S × R = Stimulus Relation × Response Relation interaction effects ($SRE_{RR} - SRE_{RC}$; see Table 1) per block type; CA = contingency awareness scores per block type; SRE = stimulus repetition effects. $R^2 = .06$ for positive versus neutral contrast; $R^2 = .003$ for negative versus neutral contrast.
* $p < .05$. ** $p < .01$. *** $p < .001$.

sions revealed a significant influence of contingency awareness on the difference in S–R binding and retrieval effects (both $|t| < 1.87$, *ns*), indicating that different levels of contingency awareness did not influence the strength of S–R retrieval effects. Importantly, the regression constant was significant in both analyses, positive vs. neutral: $c = 32.95$, $t(58) = 5.69$, $p < .001$; negative vs. neutral: $c = -14.48$, $t(58) = 2.66$, $p = .01$, indicating that even when subjective contingency awareness is zero, there are still highly significant differences in the strength of S–R binding/retrieval effects between blocks.

Funneled Debriefing

Based on their responses in the funneled debriefing, 10 participants were considered to be aware of the contingency manipulation (see Table 2). To assess whether probe results differed for aware versus unaware participants, we conducted a 2 (Stimulus Relation) × 2 (Response Relation) × 3 (Block Type) × 2 (Awareness) mixed-models ANOVA on probe RTs. Importantly, the four-way interaction was not significant, $F(2, 56) = 1.91$, $p = .15$, $\eta_p^2 = .06$, suggesting that the differences in S–R binding/retrieval effects occurred independently of whether participants could correctly identify contingencies within each block or not. Even when responses for hard to identify "no contingency" blocks were excluded, we still found a significant moderation by block type, $F(2, 31) = 18.08$, $p < .001$, $\eta_p^2 = .54$, for the subgroup of participants ($n = 33$) who were totally unaware of the direction of our contingency manipulations.

Discussion

We examined whether processes of S–R binding and retrieval adapt to contextual affordances or whether they operate independently of contingency manipulations. The present results show that S–R binding and retrieval is *context sensitive*: Compared to a neutral condition, S–R binding/retrieval effects were boosted or reduced in situations in which reliance on S–R bindings was advantageous (positive contingency) or detrimental (negative contingency) for performance, respectively. This observation is consistent with existing evidence that experimental contexts influence to which extent performance is affected by episodic retrieval processes (Frings & Wentura, 2008; Kane et al., 1997; Lowe, 1979) and demonstrates that the same principles apply to the retrieval of transient bindings between stimuli and responses.

Notably, the modulating effect of contingency on the strength of S–R binding and retrieval processes was neither mediated, nor moderated by participants' contingency awareness. We therefore conclude that participants showed a context-dependent modulation of S–R binding and retrieval effects although they were mostly unaware of S–R contingency relations in the present study. This insight is important in two respects. First, it shows that awareness or explicit insight into contingency relations is no necessary condition for a flexible adaption of episodic binding and retrieval processes. Second, it highlights that S–R binding/retrieval effects are not the product of strategic processes by which participants deliberately utilize contextual affordances for their advantage. Instead, the present findings indicate that processes of S–R binding and retrieval are *implicitly tuned* to adapt to context conditions that either promote or hinder the establishment of S–R bindings and their employment for stimulus-based action control.

Limitations

One could interpret the present results as a context-specific modulation of more superficial response heuristics: Positive (negative) contingencies might have made participants more (less) prone to adopt the "bypass rule" (repeat [switch] response in case of stimulus repetitions [switches]; Fletcher & Rabbitt, 1978). Although we cannot rule out this alternative explanation with our current data, we feel confident that our findings reflect genuine processes of S–R binding/retrieval and their modulation by contingencies because we could show in a previous study using a similar paradigm that S × R interactions were unaffected by inserting "intervening trials" between prime and probe episodes (Frings & Rothermund, 2011), which rules out explanations in terms of simple response heuristics.

As another caveat, one may question which process—binding or retrieval—is most likely affected by the context manipulation. Our data do not allow us to disentangle these two processes: Due to the delayed test of binding effects during the probe trial, S × R interactions always reflect a combination of binding and retrieval processes. Variations in the strength of this effect due to different S–R contingencies, however, may indicate differences in binding, retrieval, or both processes. Separating these two processes requires manipulations that target binding and retrieval with clearly distinct experimental manipulations (e.g., increasing the overall amount of response repetitions orthogonally to S–R contingencies should strengthen retrieval processes without affecting binding; Kane et al., 1997).

Theoretical Implications

The fact that S–R binding and retrieval effects (a) were obtained even in orthogonal blocks of the present study and elsewhere (Frings et al., 2007; Giesen & Rothermund, 2011, 2014a; Hommel, 1998; Mayr & Buchner, 2006; Moeller et al., 2012; Rothermund et al., 2005) and (b) were only reduced, but neither neutralized nor reversed in negative contingency blocks is noteworthy: It suggests that there is a strong preference or "default" to associate stimulus repetitions (changes) with response repetitions (changes) that is only slowly and reluctantly departed from. Although speculative, we would expect this to be a byproduct of our everyday experience in which stimuli and responses are strongly correlated (even irrelevant stimuli consistently require the same response due to their co-occurrence with relevant stimuli). The cognitive system is sensitive for the detection of these covariations and regularities in the environment (Garner & Felfoldy, 1970) and exploits this correlational structure to implicitly coordinate behavior (Reber, 1989).

The present study is also important for related phenomena of associative learning. There is a structural resemblance between transient effects of S–R binding and retrieval and more persistent effects of associative learning like Pavlovian conditioning (for a discussion, see Giesen & Rothermund, 2014a). According to propositional accounts, learning can only occur when participants are aware of the relations between relevant events; consequently, contingency awareness is essential to obtain Pavlovian conditioning effects (for reviews, see De Houwer, 2009; Lovibond & Shanks, 2002; Mitchell, De Houwer, & Lovibond, 2009). However, participants might have been (subjectively) unaware of the relationship between stimuli and responses, even though they were aware of the stimuli/responses themselves and, thus, were (objectively) able to infer S–R contingencies (Shanks & St. John, 1994). This would imply that subjective contingency awareness is no necessary precondition for associative learning and retrieval, since strong context-specific modulations of S–R binding and retrieval effects were obtained independently and even in the absence of subjective contingency awareness.

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Received April 2, 2015
Revision received June 9, 2015
Accepted July 13, 2015 ■