Context modulation of learned attention deployment

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Published online: 8 June 2017
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Abstract In three experiments, we investigated the contextual control of attention in human discrimination learning. In each experiment, participants initially received discrimination training in which the cues from Dimension A were relevant in Context 1 but irrelevant in Context 2, whereas the cues from Dimension B were irrelevant in Context 1 but relevant in Context 2. In Experiment 1, the same cues from each dimension were used in Contexts 1 and 2, whereas in Experiments 2 and 3, the cues from each dimension were changed across contexts. In each experiment, participants were subsequently shifted to a transfer discrimination involving novel cues from either dimension, to assess the contextual control of attention. In Experiment 1, measures of eye gaze during the transfer discrimination revealed that Dimension A received more attention than Dimension B in Context 1, whereas the reverse occurred in Context 2. Corresponding results indicating the contextual control of attention were found in Experiments 2 and 3, in which we used the speed of learning (associability) as an indirect marker of learned attentional changes. Implications of our results for current theories of learning and attention are discussed.

Keywords Attention · Context · Discrimination learning · Humans

Prior experience changes the ease with which we learn about a stimulus. Such changes in associability are demonstrated, for instance, by the intradimensional/extradimensional shift (ID/ED shift) effect (for surveys, see Le Pelley, 2004; Le Pelley, Mitchell, Beesley, George, & Wills, 2016; Pearce & Mackintosh, 2010). In one demonstration of the effect, Uengoer and Lachnit (2012) trained human participants to categorize stimuli that varied on two dimensions (e.g., color and shape). For solution of the discrimination problem, two values from one dimension were relevant, since they consistently signaled the category of the stimuli, while two values from another dimension were irrelevant, because they were unrelated to category membership (e.g., red squares and red circles belonged to one category, while blue squares and blue circles belonged to another category). Subsequently, participants received a second discrimination in which the stimuli were characterized by novel values from the previous dimensions (e.g., green, yellow; triangle, diamond). Uengoer and Lachnit observed that the second discrimination was acquired more rapidly when it was based on values from the dimension that had previously been trained as relevant for the first discrimination (ID shift; e.g., colors green and yellow signaled category membership) than when it was based on the previously irrelevant dimension (ED shift; e.g., shapes triangle and diamond signaled category membership). This effect suggests that training of the initial discrimination resulted in more attention being paid to stimulus features belonging to the relevant than to those belonging to the irrelevant dimension, and that these changes in attention were transferred to the stimuli of the second discrimination, which facilitated acquisition of the ID shift discrimination relative to the ED shift condition (e.g., Mackintosh, 1975). The assumption that discrimination learning involves changes in attention to relevant and irrelevant stimuli has been further

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supported by studies using measures of eye gaze (e.g., Le Pelley, Beesley, & Griffiths, 2011; Lucke, Lachnit, Koenig, & Uengoer, 2013; Mitchell, Griffiths, Seetoo, & Lovibond, 2012) and neurophysiological markers (e.g., Feldmann-Wüstefeld, Uengoer, & Schubö, 2015).

Uengoer, Lachnit, Lotz, Koenig, and Pearce (2013) and George and Kruschke (2012) demonstrated that changes in associability can come under the control of contextual stimuli. In their experiments, participants were initially trained with a conditional discrimination involving two contexts. In Context 1, the discrimination was solvable on the basis of cues from Dimension A, while cues from Dimension B were irrelevant. In Context 2, the same set of cues comprised a discrimination for which Dimension B was relevant and Dimension A was irrelevant. Following this training, participants received a second discrimination in which novel cues from Dimension A were relevant, and novel cues from Dimension B were irrelevant. Participants were found to master the second discrimination more rapidly when training was given in Context 1 than when trained in Context 2. This finding indicates that the associability of (and, by inference, attention to) the stimuli varied according to the context in which they were presented. More precisely, it suggests that in Context 1, cues from Dimension A possessed greater associability than those from Dimension B, and in Context 2, the opposite applied—greater associability of Dimension B than of Dimension A.

In real life, humans and other animals deal with a great variety of tasks, and the stimuli that are relevant to accomplish a certain task may be unimportant for successful performance in another situation. For instance, when looking for a friend in a crowd of people, it may be advantageous to attend to clothing color, whereas, when searching for a book in a crowded library, clothing color provides no useful information. In view of this, the ability of context-specific attention (George & Kruschke, 2012; Uengoer et al., 2013) appears to be an obvious way in which organisms may deal with the ever-changing demands in their environments. However, many theories of learning and attention neglected the context as a modulator for stimulus processing (e.g., Kruschke, 1992; Le Pelley, 2004; Mackintosh, 1975; Pearce, George, & Redhead, 1998; Pearce & Mackintosh, 2010). Thus, these models are unable to capture the possibility that a stimulus may receive considerable attention in one context, yet be ignored in a different context.

The aim of the present study was twofold. One aim was to assess the validity of the conclusion in terms of context-specific attention drawn from the studies by Uengoer et al. (2013) and George and Kruschke (2012). In these two previous studies, contextual control of attention during initial training was inferred from subsequent differences in learning rates. If this inference is valid, then it should be possible to arrive at the same conclusion using other indicators of attention. Therefore, Experiment 1 was based on the procedures used by Uengoer et al. and George and Kruschke, but in addition,

we included measures of eye gaze as a marker of attention. By means of this measure, we investigated whether training a stimulus as relevant in one context, but irrelevant in another context, results in corresponding changes in overt attention, and we explored whether changes in overt attention are transferred to novel stimuli in a context-specific manner.

A second aim of the present study, which was pursued in Experiments 2 and 3, was to investigate the role of associative interference for the formation of context-specific changes in associability. Consider a study by Griffiths and Le Pelley (2009), who found no evidence that changes in associability are modulated by contextual changes using a blocking procedure. In a typical blocking experiment (Kamin, 1968), an individual stimulus is repeatedly paired with an outcome (A+) before it is presented in compound with a second stimulus, B. This compound stimulus is also repeatedly followed by the outcome (AB+). During a final test, it can be observed that responding to Stimulus B by itself is weaker than for a control group in which pretraining with Stimulus A was omitted. It is said that learning about Stimulus B was *blocked* by the prior training of Stimulus A.

For both humans and nonhuman animals, it was found that subsequent learning about a previously blocked stimulus was retarded (Kruschke & Blair, 2000; Mackintosh & Turner, 1971), indicating that blocking involves a reduction of attention to the blocked stimulus. On the basis of this finding, Griffiths and Le Pelley (2009) examined whether the rate of new learning about a previously blocked stimulus can be modulated by contextual manipulations. During an initial phase, participants received training in which individual stimuli were paired with an outcome (e.g., A→O1, C→O1, E→O1). During a second phase, each of the stimuli was presented in compound with a novel stimulus, and these compounds were also paired with the outcome (e.g., AB→O1, CD→O1, EF→O1). Following this blocking treatment, participants received a third phase of training in which stimulus compounds signaled a new outcome. Some of these compounds comprised stimuli that had already been presented together during Phase 2 (*old* compounds—e.g., AB), whereas other compounds comprised one blocking stimulus and one blocked stimulus that had been trained on separate occasions during the preceding phase (*new* compounds—e.g., ED). Griffiths and Le Pelley observed that learning about the new outcome in Phase 3 proceeded more slowly for the blocked stimuli (e.g., B, D) than for the blocking stimuli (e.g., A, E), indicating that their blocking procedure led to a decrease of attention to the blocked stimuli. More crucially, they also reported that the impairment of learning about the

blocked stimuli in Phase 3 was independent of whether the blocked stimuli were presented in old or in new compounds. This finding is consistent with the view that attention to a stimulus is not controlled by the context in which it appears.

In the experiment by Griffiths and Le Pelley (2009), the stimuli were trained as either predictive (blocking stimuli) or redundant (blocked stimuli). Thus, the significance of the stimuli remained unchanged throughout the blocking treatment. In contrast, Uengoer et al. (2013) and George and Kruschke (2012) used conditional discriminations in which the stimuli were explicitly trained as being both relevant and irrelevant, depending on the context. Uengoer et al. suggested that such explicit training in which the significance of a stimulus changes according to context may be necessary for the formation of contextual control of stimulus associability (for a similar suggestion, see George & Kruschke, 2012). The aim of Experiments 2 and 3 was to test this proposal.

Experiment 1

In Experiment 1, we recorded gaze position as a measure of overt attention, in order to examine the contextual control of attention. In each learning trial (see Fig. 1), participants were presented with a stimulus array consisting of two cue cues from two dimensions A and B (letter and shape), presented above and below fixation, and two peripheral stimuli of different colors to the left and right of fixation (the context and control stimuli). The control stimulus, which was the same on every trial, served as a reference to assess eye gaze toward the context.

The learning schedule for Experiment 1 is shown in Table 1. In Stage 1, participants received a conditional discrimination involving two contexts. In Context 1, correct responding (R1 or R2) was predictable on the basis of two

Table 1 Design of Experiment 1

Stage	Block	Context	Discrimination
1	1, 3, 5	C1	A1B1 →R1, A1B2 →R1 A2B1 →R2, A2B2 →R2
	2, 4, 6	C2	A1B1 →R1, A1B2 →R2 A2B1 →R1, A2B2 →R2
2	7, 9	C1	A3B3 →R1, A4B4 →R2
	8, 10	C2	A5B5 →R1, A6B6 →R2

Contexts C1 and C2 are squares in different colors. A and B refer to the stimulus dimensions shapes and letters (counterbalanced), and related indices assign specific values of a dimension. R1 and R2 are different responses (single and double mouse-clicks). Relevant cues are shown in bold.

cues from Dimension A (A1 and A2), while two cues from Dimension B (B1 and B2) were irrelevant. In Context 2, the same set of cues comprised a discrimination that was solvable on the basis of the cues from Dimension B, while those from Dimension A were irrelevant.

In Stage 2, which used another set of cues from each dimension, participants were trained with two optional-shift discriminations. In Context 1, the compounds A3B3 and A4B4 were related to the responses R1 and R2, respectively, and in Context 2, R1 and R2 were signaled by the compounds A5B5 and A6B6, respectively. Thus, in Stage 2, the discrimination in each context was optional, in the sense that it was solvable on the basis of either Dimension A or Dimension B, or both.

If training of the conditional discrimination in Stage 1 resulted in context-dependent attention that was transferred to the cues from Stage 2, then Dimension A would receive more overt attention than Dimension B in the case of the optional-shift discrimination in Context 1 of Stage 2, whereas Dimension B would capture more overt attention than Dimension A as participants worked on the optional-shift discrimination in Context 2 of the second stage.

Method

Participants Thirty-three students at Philipps-Universität Marburg participated in the experiment and received either course credit or payment. All participants had normal or corrected-to-normal vision. The data of three participants were excluded from further analysis because of signal noise or excessive blinking. The data of four participants were excluded because their response accuracy did not exceed 60% in at least one of the two contexts in Stage 1. Of the remaining participants, 21 were female and five were male. Their ages ranged from 18 to 29 years, with a median of 21.

Apparatus Testing took place in a sound-attenuated, dimmed room. Monocular eye movements were recorded using an infrared video-based eyetracker (EyeLink 2000, SR

Fig. 1 Sequence of events in a trial of Experiment 1

Research) that sampled the position of the pupil and corneal reflection at 1000 Hz. Sampling of the left versus the right eye was counterbalanced across participants. The eyetracker was calibrated with a 9-point grid of calibration targets. The calibration procedure was rerun until subsequent validation confirmed an average calibration error $<0.5^\circ$. The eyetracker restrained the participant's head via chin and forehead rests and was table-mounted in front of a 22-in. CRT monitor (Iiyama, Vision Master Pro514), yielding an eye-to-screen distance of 78 cm. Stimulus delivery was controlled by the Presentation software (www.neurobs.com).

Stimuli Visual stimuli were presented on a 60% gray background. Two colored squares were shown 130 mm to the left and right of fixation, respectively, and represented the context and control stimuli. Colors (R, G, B) were chosen from a set of red (233, 198, 175), green (198, 233, 175), and blue (170, 204, 255). A letter and a geometric shape were shown 130 mm above and below the central fixation to represent the relevant and irrelevant cues. The letters were randomly chosen from the set M, R, S, X, B, G, H, and K. As shapes we used a triangle, diamond, pentagon, star, heart, cross, rhomboid, and L-shaped figure. All letters and geometric figures were shown on a rectangular white background and had the same size, 2×2 cm, as the colored squares. All stimuli had an eccentricity of 9.46 deg of visual angle (dva) and the same probability of occurring either above or below fixation (relevant and irrelevant cues) or to the left or the right (context and control stimuli).

Procedure After participants had given written consent to take part in the experiment, written instructions were presented that exemplified the events and task demands that would occur within a trial. Eight practice trials were run prior to the actual experiment to assure that participants had understood the instructions.

Figure 1 depicts the sequence of events in a trial. The trial started with a fixation cross for 2,000 ms, which was followed by a 4,000-ms presentation of the cues (letter and shape) together with the context and control stimuli (colors). Participants were instructed to inspect the four stimuli, and eye movements were recorded to obtain measures of overt attention. Participants had to learn after which combinations of cues they had to press the mouse button once (R1), and after which combinations a double-click (R2) was required. They were instructed to withhold their responses until the occurrence of a black circular prompt stimulus. When the black circle appeared, each subsequent mouse click was registered by the occurrence of a white circle within the black circle. The time window to successfully register a response was restricted to 2,000 ms. After the time window of 2,000 ms the black circle disappeared, and a feedback screen was presented for 3,000 ms. The feedback specified the correct response

(single-/double-click) by showing one or two white circles within the black circle in the middle of the previous set of stimuli. A blank screen was then shown for a random interval of 2,000 to 4,000 ms until the next trial began.

During the entire experiment, the color of one box on the horizontal meridian was the same in all trials. The other colored box provided the context that participants had to encode in order to solve the discrimination. The positions of the two colors (left or right of fixation) randomly changed across trials. The critical feature of the trained discrimination was that the context color determined which dimension (letter or shape) was relevant and which was irrelevant for predicting the correct response.

Table 1 depicts the trial types in the present experiment. In Context 1, Cues A1 and A2, which belonged to Dimension A, were reliable predictors of a single and a double mouse-click, respectively, whereas after B1 and B2, which belonged to Dimension B, both responses were correct with the same probability. This contingency was reversed in Context 2, in which Dimension A was irrelevant and Dimension B was predictive of a correct response. Each context was in effect for a block of 16 trials, with four replications of each trial type. The two contexts alternated over the first six blocks (three blocks each), yielding a total number of 96 trials in the first stage. In the second stage, new elements of Dimensions A and B again were trained in Context 1, A3B3→R1 and A4B4→R2, and in Context 2, A5B5→R1 and A6B6→R2. However, the discriminations now were *optional*, because the correct prediction could be made by attending to either Dimension A or to Dimension B in all trials, regardless of context.

In both stages of training, we used different pseudorandom trial sequences for each participant. Trials were randomly shuffled within blocks, with the restriction that the same correct response and the same cue could occur a maximum of three times in a row. The assignment of the dimensions letters and shapes to Dimensions A and B was counterbalanced across participants, as was the assignment of specific letters and specific shapes to Cues 1 to 6 within these dimensions.

Data analysis Fixations were detected using a velocity-based algorithm with a threshold of $30^\circ/\text{s}$. The *fixation probability* was computed from the frequency of fixating a stimulus element at least once during the 4-s interval of cue and context presentation. The *fixation dwell time* was computed as the summed durations of all fixations on a stimulus element that occurred in the same interval. Repeated measures analysis of variance (ANOVA) was used to analyze the data. For this and the subsequent experiments, the .05 level of significance was employed for all statistical tests; stated probability levels are based on a Greenhouse–Geisser (1959) adjustment of degrees of freedom, where appropriate; and effect sizes were computed as generalized eta squared (Bakeman, 2005). For a focused test of our hypotheses of “more attention to relevant cues and

contexts,” we used contrast analysis. In the case of multiple testing, p values were adjusted according to Benjamini and Hochberg (1995), as is stated in the Results section.

Results and discussion

Predictive learning During training, participants learned to anticipate the correct response on 76% of all trials in the acquisition stage ($SEM = 2.724$). This level of correct responding was significantly greater than chance level, $t(25) = 9.430$, $p < .001$. However, closer inspection of performance by individual participants revealed that the percentage of correct responding followed a clear bimodal distribution, as is shown in Fig. 2.

One subgroup of participants succeeded in predicting the correct response on a high percentage of trials, whereas a second subgroup was considerably less accurate. From the empirical distribution of performance, we derived a post-hoc factor group that encoded the distinction between poor learners (<75% correct, $n = 13$) and good learners (>75% correct, $n = 13$). The probabilities of a correct response in both groups are shown in Fig. 3.

For the training stage (left panel), a 2×2 ANOVA revealed significant main effects of group, $F(1, 24) = 145.95$, $p < .001$, $\eta^2 = .70$, and context, $F(1, 24) = 24.68$, $p < .001$, $\eta^2 = .39$, that were modulated by a Group $\times$ Context interaction, $F(1, 24) = 6.70$, $p = .02$, $\eta^2 = .15$. Although good learners' performance was slightly better in Context 1 than in Context 2, $t(12) = 2.194$, $p = .049$, their probabilities of correct responding were clearly above chance level in both contexts (both $ps < .001$ for the difference from .5). Poor learners, on the other hand, were characterized by a marked performance difference between the contexts, $t(12) = 4.497$, $p < .001$. Correct responding in Context 1 was well above chance level, $t(12) = 7.285$, $p < .001$, but there was no evidence that correct responding was above chance in Context 2, $t(12) = 1.196$, $p = .127$. In the test

Fig. 2 Bimodal distribution of individual levels of correct responding in the acquisition phase of Experiment 1. Learners were classified as “poor” versus “good” on the basis of a cutoff value of 75%. Note that a score higher than 75% means that good learners responded above chance level (50%) in both learning contexts of the acquisition phase, whereas a score below or equal to 75% could have been caused by the acquisition of correct responding in one context only

Fig. 3 Probabilities of a correct response, dependent on the post-hoc factor group (good learners, poor learners), as well as the factors stage (training, test) and context (1, 2), in Experiment 1. In the training stage, poor learners specifically failed to acquire correct responses in the second context. Error bars denote standard errors of the means.

stage, good learners again performed better than poor learners, $F(1, 24) = 9.02$, $p = .006$, $\eta^2 = .25$, but no differences between contexts were evident, $F < 1$, and performance was above chance level for both groups in both contexts (all $ps < .001$).

The difference in context-modulated performance between training and test for poor learners is readily explained by the major difference between the trained discriminations. Whereas in the training stage encoding of the context stimulus was essential for correct responding in both contexts, the context could be completely ignored in the test stage. For example, if poor learners ignored the context from the very beginning of the training stage, they would have failed to detect the context changes, and in turn would have failed to disengage attention from Dimension A when it became irrelevant in Context 2. Furthermore, performance in Context 2 would have been restored in the test stage when correct prediction was possible with attention to either dimension in both contexts. Our analysis of eye movements as a measure of overt attention in the following section will shed further light on this attentional interpretation.

Attentional learning The stimulus display consisting of one letter, one shape (cue elements), and two colored squares (context and control stimuli) shown for 4 s in each trial, and participants moved their eyes to focus on some elements at the cost of neglecting other elements. We analyzed fixation probabilities and fixation dwell times in order to examine how associative learning affected measures of overt attention.

Figure 4 presents summed fixation dwell times on Cue Dimension A versus B, dependent on the learning context (1 vs. 2). The four different panels depict attentional allocation for the groups of good learners (top) and poor learners (bottom) during training (left) and test (right). A superordinate ANOVA with the factors group (poor, good), stage (train, test), context (1, 2), and dimension (A, B) revealed significant two-

Fig. 4 Fixation dwell times on the cue dimensions in Experiment 1. Error bars denote standard errors of the means

way Group $\times$ Dimension, $F(1, 24) = 7.065$, $p = .014$, $\eta^2 = .011$, and Dimension $\times$ Context, $F(1, 24) = 8.444$, $p = .031$, $\eta^2 = .008$, interactions, which were further modulated by the three-way interaction Group $\times$ Dimension $\times$ Context, $F(1, 24) = 6.058$, $p = .021$, $\eta^2 = .022$. To further elucidate the latter interaction, we conducted a planned comparison of the cell means using contrast analysis. For the ordering of factor levels shown on the x-axes in Fig. 4, the contrast weights $\lambda = [1, -1, -1, 1]$ coded for the joint hypothesis that (a) during training, participants paid more attention to the dimension that was relevant in the given context, and (b) this context-dependent attention bias transferred to the test stage. Collapsed across both stages, the contrast was highly significant in the group of good learners, $t(24) = 3.795$, $p < .001$, $r = .612$, for whom the dwell time on relevant cues exceeded the dwell time on irrelevant cues. In contrast, the same comparison of cell means was not significant in poor learners, $t(24) = 0.314$, $p < .378$, $r = .064$. As a further analysis, we tested the contrast for each combination of Group $\times$ Stage, with p values adjusted for multiple testing (Benjamini & Hochberg, 1995). For good learners, the hypothesized contrast was significant for both the training stage, $t(31) = 3.480$, $p = .002$, $r = .530$, and the test stage, $t(31) = 3.606$, $p = .002$, $r = .544$, suggesting that good learners paid more attention to the previously relevant stimulus dimension, even if this bias was no longer necessary for solving the task in Stage 2. In comparison, for poor learners, the contrast was significant neither during training, $t(31) = -0.509$, $p = .692$, $r = .091$, nor during test, $t(31) = 1.096$, $p = .187$, $r = .193$ (p values adjusted for multiple testing of four contrasts).

To further explore the actual dwell times observed in the group of poor learners, we conducted separate ANOVAs for both experimental stages. For the training stage, this analysis

revealed a main effect of dimension, $F(1, 12) = 6.442$, $p = .026$, $\eta^2 = .072$; no main effect of context, $F < 1$; and no significant interaction, $F(1, 12) = 1.1354$, $p = .307$, $\eta^2 = .003$, indicating that poor learners spent more time fixating on Dimension A, regardless of the context. The same analysis for the test stage revealed no main effect of either dimension, $F(1, 12) = 2.028$, $p = .179$, $\eta^2 = .003$, or context, $F < 1$, and no interaction $F(1, 12) = 3.412$, $p = .089$, $\eta^2 = .012$.

In summary, the analysis of total dwell times in the training stage revealed that good learners managed to use the context to focus on the relevant dimension and switched their attentional focus when the context changed. Poor learners, on the other hand, acquired an attentional bias for Dimension A that was relevant in the first block of training, but they had difficulties disengaging from Dimension A when it became irrelevant in Context 2. This difference in the contextual modulation of attention provides a ready explanation for our findings on predictive learning reported in the previous section: Good learners were able to acquire the correct predictive responses in both contexts because they learned to focus on the relevant dimension in each context. Poor learners, on the other hand, exhibited a selective retardation of correct predictive responding in Context 2 because they failed to disengage from Dimension A, and thus focused on cues that were not predictive of the correct response in the second context.

Although encoding of the context was essential for predictive learning in the acquisition stage, it was arbitrary in the test stage. The discriminations of A3B3→R1, A4B4→R2 in Context 1 and A5B5→R1, A6B6→R2 in Context 2 could have been acquired successfully without any encoding of the contexts and with a random bias for either Dimension A or B, or both, in any context. The second stage of our experiment thus provided a test for the hypothesis that the context-dependent attentional bias acquired during associative learning transferred to a learning situation in which this bias was not necessary for correct responding. The results suggest that good learners exhibited perfect transfer: In Context 1 they spent more time fixating on elements of Dimension A than of Dimension B, whereas in Context 2 their fixation dwell times were longer for Dimension B than for Dimension A. In contrast, such an effect was absent for poor learners in the test stage.

Besides the two cues (shape, letter) that were presented in each trial, the display also featured the two color stimuli, shown in Fig. 1. One color was the context color, which specified the relevant cue as being either the letter or the shape, and the other color was a constant control stimulus. Figure 5 depicts the probabilities of fixating these colors (context vs. control) at least once per trial, depending on the color of the context (1 vs. 2), for good learners (top) and poor learners (bottom) during training (left) and test (right). The first aspect to note in Fig. 5 is the overall low fixation frequencies. On average, participants moved their eyes to fixate the peripheral

Fig. 5 Probabilities of fixating the colored context and control stimuli during the 4-s interval of presentation in Experiment 1. Error bars denote standard errors of the means

colored boxes on only about 46% of all trials in the training stage, and on 40% of all trials in the test stage.

Because in the training stage encoding of the context color was essential for correct responding, and good learners exhibited a high percentage of correct responses as shown in Fig. 3, it seems that the context could have been encoded without looking at it directly, but rather by identifying its color in the visual periphery. Furthermore, with the blocked context changes used in our experiment, participants were likely to realize that after a context change, the context would be constant for the next series of trials. From this perspective, there was no need to attend to the context on each and every trial. However, on top of the rather low general fixation frequency, Fig. 5 depicts differences between the experimental conditions. A superordinate Group (poor, good) $\times$ Stage (train, test) $\times$ Color (Context, Control) $\times$ Context (1, 2) ANOVA revealed a main effect of stage, $F(1, 24) = 6.560$, $p = .017$, $\eta^2 = .022$, and a main effect of color, $F(1, 24) = 4.787$, $p = .038$, $\eta^2 = .003$, that were modulated by the interactions Group $\times$ Color, $F(1, 24) = 5.416$, $p = .028$, $\eta^2 = .004$, and Group $\times$ Color $\times$ Context, $F(1, 24) = 4.272$, $p = .049$, $\eta^2 = .001$. To further examine the three-way interaction, we conducted a planned comparison of the cell means, as we also reported for fixation dwell times above. For the ordering of factor levels shown on the x -axes in Fig. 5, the contrast weights $\lambda = [1, -1, 1, -1]$ coded for the joint hypothesis that (a) during training, participants paid more attention to the context color than to the control color, and (b) this attention bias for the context transferred to the test stage. Collapsed across both stages, this contrast was highly significant in the group of good learners, $t(24) = 3.193$, $p = .002$, $r = .545$, for whom the fixation probability for the context color exceeded

the fixation probability for the control color. In contrast, the same comparison of cell means was not significant in poor learners, $t(24) = -0.099$, $p = .538$, $r = .020$. Further analysis revealed that for good learners the contrast was significant for both the training stage, $t(44) = 2.268$, $p = .028$, $r = .323$, and the test stage, $t(44) = 2.835$, $p = .013$, $r = .391$, suggesting that good learners paid more attention to the previously relevant learning context, even if this bias was no longer necessary for solving the task in Stage 2. In comparison, for poor learners, the contrast was significant neither during training, $t(44) = -0.347$, $p = .634$, $r = .052$, nor during test, $t(44) = 0.189$, $p = .567$, $r = .029$ (p values adjusted for multiple testing of four contrasts).

In summary, the analysis of fixation frequencies revealed that good learners exhibited an attentional bias for the context color over the control color that was not evident in poor learners. For good learners, the peripheral color that indicated which cue element (letter or shape) was a good predictor of the outcome attracted gaze with higher probability than did the noninformative control color, and this attentional bias transferred to the test stage.

The results from Experiment 1 clearly support the conclusion drawn from the studies by Uengoer et al. (2013) and George and Kruschke (2012) that attention can come under the control of contextual stimuli. Participants who successfully mastered a conditional discrimination in which the cues from Dimension A were relevant in Context 1 but irrelevant in Context 2, whereas the cues from Dimension B were irrelevant in Context 1 but relevant in Context 2, showed different patterns of overt attention across the contexts during training. More precisely, cues from Dimension A received more overt attention than did those from Dimension B in Context 1, whereas the opposite pattern of overt attention was observed in Context 2. Furthermore, when subsequently presented with novel stimuli from both dimensions possessing equal predictive values, the changes in overt attention were transferred to the novel stimuli in a context-specific manner. Thus, although all the novel cues were equally relevant, the cues belonging to Dimension A received more overt attention than did those from Dimension B when they were presented in Context 1, whereas the opposite was observed in Context 2. Moreover, we found no evidence that overt attention was modulated by contextual changes in those participants who failed to successfully solve the initially trained conditional discrimination. This finding confirms that the context specificity of overt attention observed in the present experiment was related to learning experience and not to other aspects of the procedure.

Experiment 2

In Experiment 1 and the studies by Uengoer et al. (2013) and George and Kruschke (2012), context-dependent associability was induced by means of a conditional discrimination in which each cue was explicitly trained as being both relevant and irrelevant, depending on the context. The second aim of the present study was to investigate whether such explicit training in which the significance of a cue changed according to context was necessary for the formation of contextual control of associability. This question was addressed by Experiments 2 and 3.

Both experiments used a procedure adopted from Uengoer et al. (2013). For each trial, participants were shown two cues from two dimensions (A, B; letter, shape), presented side by side, and the context was provided by a colored rectangular frame surrounding the cues. Table 2 illustrates the design for the two groups of Experiment 2. Initially, all participants received discrimination training across the two contexts. In Context 1, the outcomes were predictable on the basis of two cues from Dimension A (A1 and A2), while two cues from Dimension B (B1 and B2) were irrelevant. In Context 2, the discrimination involved another set of cues from either dimension (A3, A4, B3, B4) and was solvable on the basis of those belonging to Dimension B, while Dimension A was irrelevant. Hence, the significance of each cue remained unchanged throughout training, and the discrimination was solvable on the basis of cues A1, A2, B3, and B4, while the remaining cues or the contexts were, in principle, not required for accurate performance.

In Stage 2, participants were trained with an optional-shift discrimination involving novel cues from both dimensions (A5, B6). In the optional-shift discrimination, compound A5B5 was paired with Outcome O1, and compound A6B6 with O2. Half of the participants (Group C1) received the

optional-shift discrimination in Context 1, whereas the other half (Group C2) were trained in Context 2.

To assess the way in which participants solved the optional-shift discrimination from Stage 2, transfer compounds A5B6 and A6B5 were tested in Stage 3 in either Context 1 (Group C1) or Context 2 (Group C2).

If training of the discrimination in Stage 1 induced context-dependent changes in associability, the participants in Group C1 would solve the optional-shift discrimination from Stage 2 on the basis of Dimension A, whereas the participants in Group C2 would rely on Dimension B during the second stage. As a consequence, Group C1 would show a higher proportion of Outcome 1 predictions in response to the transfer compound A5B6 than to the compound A6B5, whereas we should observe the opposite in Group C2, with a higher proportion of Outcome 1 predictions for A6B5 than for A5B6. In contrast, if the Stage 1 discrimination did not establish context-dependent associability, there should be no systematic learning bias in favor of one dimension or the other during the subsequent stages in each group. Accordingly, a difference in responding between the two transfer compounds should be observed in neither group.

To facilitate acquisition of the initial discrimination for our participants, we simplified our experimental procedure. First, recording of eye gazes was abandoned, since this measure was not necessary to assess the predictions just described for the transfer stage. In this way, we avoided the demands caused by task requirements related to gaze position recording. Second, we included a period of preliminary training in which participants were given the opportunity to acquire the Stage 1 discrimination step by step (for details, see the Method section below).

Method

Participants A group of 64 students at Philipps-Universität Marburg (of which 45 were females) participated in Experiment 2. Their ages varied between 18 and 35 years, with a median of 23. They either participated to meet course requirements or were paid for their attendance. Participants were randomly allocated to the two groups as they arrived at the experimental room. They were tested individually and required approximately 15 min to complete the experiment. For six additional participants, the experiment was terminated during a preliminary training period because they failed to complete one of the four phases of this preliminary treatment within 40 trials (see below). Furthermore, the data of two additional participants were excluded from the analyses because their predictions were incorrect on more than 30% of the eight trials presented during the first or the second half of the last block of Stage 1 (see below). Participants gave informed written consent to participate in the experiment.

Table 2 Design of Experiment 2

Stage	Context	Group C1	Group C2
1	C1	A1B1 →O1, A1B2 →O1 A2B1 →O2, A2B2 →O2	A1B1 →O1, A1B2 →O1 A2B1 →O2, A2B2 →O2
	C2	A3B3 →O1, A3B4 →O2 A4B3 →O1, A4B4 →O2	A3B3 →O1, A3B4 →O2 A4B3 →O1, A4B4 →O2
2	C1	A5B5 →O1, A6B6 →O2	A5B5 →O1, A6B6 →O2
	C2		
3	C1	A5B5→?, A5B6→? A6B5→?, A6B6→?	A5B5→?, A5B6→? A6B5→?, A6B6→?
	C2		

Contexts C1 and C2 are rectangular frames in different colors. A and B refer to the stimulus dimensions shapes and letters (counterbalanced), and related indices assign specific values of a dimension. O1 and O2 are different categories. “?” represents an absence of feedback to participants. Relevant cues are shown in bold.

Apparatus and procedure The instructions and further necessary information were presented on a computer screen. Participants interacted with the computer using the mouse. Twelve different squares (with a side length of 4 cm each) were used as the cues. Each of six of these squares displayed a white line drawing of one of six geometric shapes (circle, cross, parallelogram, pentagon, star, or triangle) on a black background. Each of the remaining squares showed one of six capital letters (G, K, M, P, S, or Y) in black font on a white background. A red and a blue rectangular frame served as Contexts 1 and 2. The frames were 24 cm wide and 12 cm high. The two different outcomes were the numbers 1 (O1) and 2 (O2). For each group, the stimuli were counterbalanced as follows. Half of the participants received the red frame as Context 1 and the blue frame as Context 2, whereas for the other half the blue frame served as Context 1 and the red frame as Context 2. For half of the participants in each of these two context conditions, Cues A1 to A6 represented the six geometric shapes, and Cues B1 to B6 represented the six capital letters. For the other half, Cues A1 to A6 represented the letters, and Cues B1 to B6 represented the shapes. Both the assignment of specific letters or shapes to Cues A1 to A6 and the assignment of specific shapes or letters to Cues B1 to B6 were implemented randomly for each participant.

Each participant was initially asked to read the following instructions (in German) on the screen:

This study is concerned with the question of how people learn about relationships between different events. In the following experiment, you will be shown a succession of different figures. Each figure is composed of two symbols surrounded by a colored frame. Moreover, each figure belongs to a specific category: Category 1 or Category 2. Your task is to find out which figures belong to Category 1 and which figures belong to Category 2. To solve this task, you will be shown different figures one after the other. For each figure, you should predict whether it belongs to Category 1 or Category 2. For this prediction, there will be two response buttons available. After you have made your prediction, you will be informed about the category membership of the figure. Use this feedback to discover which figures belong to Category 1 and which figures belong to Category 2. Obviously, at first you will have to guess, as you do not know anything about the criteria for categorization. But eventually you will find out according to which criteria the figures are assigned to the categories. On the basis of this knowledge,

you should make correct predictions—as many as possible.

For all of your answers, accuracy rather than speed is essential. Please do not take any notes during the experiment. If you have any more questions please ask them now. If you don't have any questions, please start the experiment by clicking on the *Next* button.

On each trial, two squares, displaying one shape and one letter, were shown in the top half of the screen. The two squares were presented side by side, with the left–right allocation of shape and letter being determined randomly on each trial. Each square appeared at a distance of 4 cm from the vertical center of the display. The squares were surrounded by a rectangular frame in either red or blue. Participants were asked to predict the category membership of the stimulus configuration by clicking on one of two answer buttons, labeled “1” or “2.” Immediately after they had responded, another window appeared telling participants the category membership of the stimulus configuration. Participants had to confirm that they had read the feedback by clicking on an “OK” button. Subsequently, the next trial started.

During Stage 1, all participants received discrimination training in two different contexts. In Context 1, Cues A1 and A2 signaled category membership, while Cues B1 and B2 were irrelevant. In Context 2, the task was based on Cues B3 and B4, while Cues A3 and A4 were irrelevant. Stage 1 comprised 80 trials and was divided into five blocks, each of 16 trials. Within each block, the four trial types related to the same context were presented on eight consecutive trials, with each trial type presented twice in a random order. Whether a block started with trials in Context 1 or Context 2 was determined randomly for each block and each participant, except for the final block of Stage 1. In this case, the order of contexts was counterbalanced across participants.

A period of preliminary training was given prior to Stage 1, in order to facilitate acquisition of the discriminations (e.g., Mitchell et al., 2012; Uengoer et al., 2013). There were four phases of this preliminary treatment (Phase Ctx1/a: Context 1: A1→O1, A2→O2; Phase Ctx1/ab: Context 1: A1B1→O1, A1B2→O1, A2B1→O2, A2B2→O2; Phase Ctx2/b: Context 2: B3→O1, B4→O2; Phase Ctx2/ab: Context 2: A3B3→O1, A3B4→O2, A4B3→O1, A4B4→O2). Each preliminary phase comprised at least one block of eight trials. The number of additional blocks given to a participant depended on their prediction accuracy. Within each block of Phases Ctx1/a and Ctx2/b, each of the two trial types was presented four times in a random order; within each block of Phases Ctx1/ab and Ctx2/ab, each of the four trial types was presented twice in a random order. If participants accomplished one block of a phase without an incorrect prediction, the next phase was initiated. Otherwise, the phase was repeated for a further block. If participants failed to complete one phase

within 40 trials (five blocks), the experiment was terminated. Phase Ctx1/a was always followed by Phase Ctx1/ab, and Phase Ctx2/b was always followed by Phase Ctx2/ab. Whether preliminary training commenced in Context 1 or in Context 2 was counterbalanced across the participants in each group. Stage 1 started immediately after the completion of the four preliminary phases.

After participants had completed Stage 1, they immediately received a discrimination with A5B5→O1 and A6B6→O2 trials. Thus, outcomes during this stage were predictable on the basis of Cues A5 and A6, as well as on the basis of Cues B5 and B6. For half of the participants, this discrimination training was conducted in Context 1 (Group C1), whereas for the other half, training took place in Context 2 (Group C2). Stage 2 comprised five blocks, each of four trials. Within each block, each of the two trial types was presented twice in a random order.

Following Stage 2, participants received a series of test trials with A5B5, A5B6, A6B5, and A6B6, presented in either Context 1 (Group C1) or Context 2 (Group C2). This test was introduced by the following instructions: “Now the feedback telling you the correct category membership of a figure will be omitted. Nevertheless, please exert yourself to predict which figures belong to Category 1 and which figures belong to Category 2.” The setup of the test trials was identical to that of the previous trials, with the exception that the feedback window was omitted. The test stage comprised 24 trials and was divided into three blocks, each of eight trials.

Within each block, each of the four trial types was presented twice in a random order.

Results and discussion

The left-hand panel of Fig. 6 presents the mean proportions of correct predictions across the five blocks of Stage 1, separated by group and context. As can be seen, participants showed a high level of accuracy throughout Stage 1, indicating the effectiveness of the preliminary exercise phase. Most importantly, performance during Stage 1 did not differ across groups and contexts.

This was confirmed by a $2 \times 5 \times 2$ repeated measures ANOVA on the proportions of correct predictions, including the within-subjects factors context (1 vs. 2) and block (1–5), and the between-subjects factor group (C1 vs. C2). The analysis revealed no main effect of block, $F(4, 248) = 1.59$, $p = .19$, yielding no evidence that the level of accuracy changed in the course of Stage 1 training. The main effects of context and group, and all interactions including either or both of these factors, were not significant, all F s < 1.38 , indicating that performance did not differ significantly across contexts and groups.

The right-hand panel of Fig. 6 shows the mean proportions of correct predictions across the five blocks of Stage 2, separated by groups. A Block (1–5) $\times$ Group (C1 vs. C2) ANOVA on the proportions of correct predictions revealed a main effect of block, $F(4, 248) = 51.55$, $p < .001$, $\eta^2 = .364$, indicating

Fig. 6 Mean proportions of correct predictions across the five blocks of Stage 1 (left panel) and the five blocks of Stage 2 (right panel) in Experiment 2, separated by groups and contexts

that the accuracy of predictions increased across the blocks of Stage 2. Neither the main effect of group nor the Block $\times$ Group interaction was significant, both F s < 1.84 , showing that performance during Stage 2 did not differ significantly between Contexts 1 and 2.

Figure 7 presents the performance of our participants during the test stage, in which feedback about the outcomes was omitted. The data shown are the mean proportions of Outcome 1 predictions across the six presentations of each trial type, separated by groups.

For the compounds that had already been trained in Stage 2, A5B5 and A6B6, all participants responded during the test stage according to the contingencies that they had experienced in the previous phase. A Cue (A5B5 vs. A6B6) $\times$ Group (C1 vs. C2) ANOVA on the proportions of Outcome 1 predictions revealed a main effect of cue, $F(1, 62) = 482.35$, $p < .001$, $\eta^2 = .877$, showing a higher proportion of Outcome 1 predictions to A5B5 than to A6B6. The main effect of group and the Cue $\times$ Group interaction were not significant, both F s < 1 , indicating no evidence of a difference in discrimination performance across the groups.

In the case of the transfer compounds A5B6 and A6B5, the two groups showed opposite patterns of discrimination performance during the test stage. A Cue (A5B6 vs. A6B5) $\times$ Group (C1 vs. C2) ANOVA on the proportions of Outcome 1 predictions revealed neither a main effect of cue nor a main effect of group, both F s < 1 , but a significant Cue $\times$ Group interaction,

$F(1, 62) = 17.22$, $p < .001$, $\eta^2 = .212$, indicating that discrimination between the cues varied across groups. We found that the participants in Group C1 predicted Outcome 1 with a higher proportion for A5B6 than for A6B5, $t(31) = 2.59$, $p = .015$, whereas the participants in Group C2 showed the opposite pattern, with a higher proportion of Outcome 1 predictions for A6B5 than for A5B6, $t(31) = -3.35$, $p = .002$.

Overall, after having acquired a discrimination in which two cues from Dimension A were relevant in Context 1 and two other cues from the same dimension were irrelevant in Context 2, whereas two cues from Dimension B were irrelevant in Context 1 and two other cues from the dimension were relevant in Context 2, participants solved a second discrimination, in which the novel cues from both dimensions were equally relevant, in different ways, depending on the context. When the second discrimination was given in Context 1, participants more readily learned about the cues from Dimension A than those from Dimension B, whereas in Context 2, learning took place more readily about cues from Dimension B than those from Dimension A. This finding is consistent with the view that the initial training resulted in context-specific changes in associability: In Context 1, the associability of cues from Dimension A was greater than that of cues from Dimension B, whereas in Context 2, the cues from Dimension B possessed greater associability than those from Dimension A.

Fig. 7 Mean proportions of Outcome 1 predictions across the four trial types presented during Stage 3 of Experiment 2, collapsed across the six presentations of each trial type within each group. Error bars denote standard errors of the means

Our finding is inconsistent with a proposal put forward by Uengoer et al. (2013) that context-specific changes in associability may only emerge under conditions in which the significance of a cue changes according to the context (see also George & Kruschke, 2012). To our knowledge, Experiment 2 has been the first to provide evidence that changes in associability during discrimination learning can come under the control of contextual stimuli in the absence of associative interference. To demonstrate the reliability of our finding, the purpose of Experiment 3 was to provide additional evidence for our conclusion by using another kind of test procedure.

Experiment 3

The design of Experiment 3 is shown in Table 3. Stage 1 of the experiment was identical to that of Experiment 2. Thus, two groups of participants were initially trained with a discrimination involving two contexts; two cues from Dimension A were relevant in Context 1, whereas another pair of cues from this dimension was irrelevant in Context 2, and two cues belonging to Dimension B were irrelevant in Context 1, whereas another pair of cues from this dimension was relevant in Context 2. In Stage 2, participants received a discrimination composed of novel cues from both dimensions, in which Dimension A was relevant and Dimension B was irrelevant. For half of the participants (Group C1), the discrimination in Stage 2 was conducted in Context 1, whereas for the other half (Group C2), the training in Stage 2 took place in Context 2. If, as we concluded from the previous experiment, the original training results in context-dependent changes in associability, then during Stage 2, the irrelevant Dimension B would initially possess greater associability than the relevant Dimension A in Group C2, which should impair acquisition of the discrimination as compared to Group C1, in which the relevant dimension should have greater

associability than the irrelevant dimension from the outset of Stage 2.

Method

Participants Another group of 64 students at Philipps-Universität Marburg (of which 39 were females) participated in Experiment 3. Their ages varied between 20 and 53 years, with a median of 23. Participants either attended in order to meet course requirements or were paid with sweets. They were randomly allocated to two groups as they arrived at the experimental room, and they were tested individually. Participants required approximately 15 min to complete the experiment. For four additional participants, the experiment was terminated during a preliminary training period because they failed to complete one of four phases of the preliminary treatment within 40 trials. Furthermore, the data of one additional participant were excluded from the analyses because of incorrect predictions on more than 30% of the eight trials presented during the first or the second half of the last block of Stage 1. All participants gave informed written consent to participate in the experiment.

Apparatus and procedure The instructions, stimuli, and procedure were identical to those aspects of Experiment 2, unless stated otherwise. Following Stage 1, all participants immediately received a discrimination based on Cues A5 and A6, whereas Cues B5 and B6 were irrelevant. For half of the participants, this discrimination training was conducted in Context 1 (Group C1), whereas for the other half, training took place in Context 2 (Group C2). Stage 2 comprised five blocks, each of eight trials. Within each block, each of the four trial types was presented twice in a random order.

Results and discussion

The left-hand panel of Fig. 8 presents the mean proportions of correct predictions across the five blocks of Stage 1, separated by group and context. A Context (1 vs. 2) $\times$ Block (1–5) $\times$ Group (C1 vs. C2) ANOVA revealed a main effect of block, $F(4, 248) = 4.70, p = .003, \eta^2 = .021$. All other main effects or interactions were not significant, $F_s < 1.72$.

The right-hand panel of Fig. 8 presents the mean proportions of correct predictions across the five blocks of Stage 2 for each group. A Block (1–5) $\times$ Group (C1 vs. C2) ANOVA revealed a main effect of block, $F(4, 248) = 42.16, p < .001, \eta^2 = .269$, and a main effect of group, $F(1, 62) = 4.07, p = .048, \eta^2 = .029$, reflecting that the accuracy of predictions was higher in Group C1 than in Group C2. The Block $\times$ Group interaction was not significant, $F(4, 248) = 1.28, p = .29$.

After a discrimination in which the cues from Dimension A and Dimension B were trained as relevant and irrelevant, respectively, in Context 1, whereas the other cues from

Table 3 Design of Experiment 3

Stage	Context	Group C1	Group C2
1	C1	A1B1 →O1, A1B2 →O1 A2B1 →O2, A2B2 →O2	A1B1 →O1, A1B2 →O1 A2B1 →O2, A2B2 →O2
	C2	A3B3 →O1, A3B4 →O2 A4B3 →O1, A4B4 →O2	A3B3 →O1, A3B4 →O2 A4B3 →O1, A4B4 →O2
2	C1	A5B5 →O1, A5B6 →O1 A6B5 →O2, A6B6 →O2	A5B5 →O1, A5B6 →O1 A6B5 →O2, A6B6 →O2
	C2		A5B5 →O1, A5B6 →O1 A6B5 →O2, A6B6 →O2

Contexts C1 and C2 are rectangular frames in different colors. A and B refer to the stimulus dimensions shapes and letters (counterbalanced), and related indices assign specific values of a dimension. O1 and O2 are different categories. Relevant cues are shown in bold.

Fig. 8 Mean proportions of correct predictions across the five blocks of Stage 1 (left panel) and the five blocks of Stage 2 (right panel) in Experiment 3, separated by groups and contexts

Dimension A and Dimension B were irrelevant and relevant, respectively, in Context 2, a second discrimination, in which novel cues from Dimension A were relevant and novel cues from Dimension B were irrelevant, was acquired more rapidly when it was conducted in Context 1 than in Context 2. Consistent with the previous experiment, the results from Experiment 3 support the conclusion that changes in associability during discrimination learning can come under the control of context, even under conditions in which the contextual information is not essential for successful acquisition.

General discussion

In each of three experiments, we found evidence that attention can be modulated by context. In the initial phase of each experiment, participants received a discrimination for which cues from Dimension A were relevant in Context 1 but irrelevant in Context 2, whereas cues from Dimension B were irrelevant in Context 1 but relevant in Context 2. In Experiment 1 we used the same set of cues in Contexts 1 and 2, whereas in Experiments 2 and 3, different cues were presented across the contexts. Following initial training, the participants in each experiment were trained with a transfer discrimination involving novel cues from both dimensions. In Experiments 1 and 2 the transfer discrimination was optional, since it was solvable on the basis of either Dimension A or B (or both), whereas for the transfer discrimination in

Experiment 3, Dimension A was relevant and Dimension B was irrelevant.

In Experiment 1, measures of eye gaze showed that Dimension A received more overt attention than Dimension B when the transfer task was given in Context 1, whereas the opposite pattern of overt attention was found in Context 2. The results from the transfer discrimination in Experiment 2 revealed that the discrimination was solved on the basis of Dimension A when it was trained in Context 1, but on the basis of Dimension B in Context 2. In Experiment 3, we observed that the transfer discrimination was acquired more rapidly when it was performed in Context 1 than in Context 2.

The finding that attention can be brought under contextual control had been documented in previous studies by Uengoer et al. (2013) and George and Kruschke (2012). The present experiments go beyond these previous studies in two important ways. First, because we recorded eye gaze as a marker of attention, Experiment 1 provided converging evidence for context-specific attention, which is strong support for the validity of the conclusions drawn from the studies by Uengoer et al. and George and Kruschke. Second, Experiments 2 and 3 demonstrated contextual control of stimulus associability despite the absence of associative interference on the level of individual cues.

The results from Experiments 2 and 3 indicate that associative interference is not a necessary condition for the formation

of context-modulated attention, contrary to proposals that Uengoer et al. (2013) and George and Kruschke (2012) put forward to reconcile their findings with those reported by Griffiths and Le Pelley (2009), who found no evidence that associability is influenced by contextual changes. However, the present Experiments 2 and 3 featured another source of interference: context-dependent alternations in the significance of entire stimulus dimensions. Such a source of interference was absent in the study by Griffiths and Le Pelley, which may be an important procedural difference that is responsible for the diverging results. For example, during training of the initial discriminations in Experiments 2 and 3, participants may have, at first, transferred changes in attention that were encouraged by training in one context to the different cues trained in the other context. Such transfer of attentional changes from one context to the other would be detrimental for accurate performance during the first experimental stage, which may have encouraged the formation of contextual control of attention to overcome this source of interference.

The present study is challenging for many theories of learning and attention (e.g., Kruschke, 1992; Le Pelley, 2004; Mackintosh, 1975; Pearce et al., 1998; Pearce & Mackintosh, 2010). Our results are in keeping with the general principle adopted by these models that relevant cues receive more attention than irrelevant stimuli, and that these differences in attention influence the ease with which learning about the stimuli takes place. However, these theories characterize attention to a stimulus in a context-independent manner, and are, therefore, unable to deal with the present results indicating that attention can come under contextual control. In the following paragraphs, we present two of these theories in more detail—the theory of attention developed by Mackintosh (1975), and Kruschke’s (1992) ALCOVE model.

Mackintosh (1975) proposed that attention to a stimulus will increase if an outcome is predicted more accurately on the basis of this stimulus than on the basis of all other stimuli concurrently present, whereas attention to a stimulus will decrease if an outcome is predicted more accurately by other accompanying stimuli. Mackintosh assumed that changes in both associative strength and attention occur to individual cues. The model adopts an elemental view of stimulus representation in which specific combinations of stimuli are not encoded. Thus, successful acquisition of the conditional discrimination from Experiment 1 lies outside the scope of the model. Therefore, our first experiment may be considered as not appropriate for assessing the theory. However, acquisition of the initial discrimination from Experiments 2 and 3 poses no challenge for Mackintosh’s theory as it is solvable on the basis of

four individual cues (A1, A2, B3, B4). According to the model, training of the discrimination will result in considerable attention to the four relevant cues, whereas the remaining cues and the contexts will undergo decreases in attention, which makes it impossible for the model to account for the differences in learning during the transfer discrimination observed in each of the Experiments 2 and 3.

Kruschke’s (1992) ALCOVE model can deal with each of the initial discriminations in the present study. This configural model assumes a stimulus representation that characterizes stimuli as points in a multidimensional psychological space. The input layer consists of nodes, each corresponding to a single psychological dimension, and is connected to a hidden layer of nodes representing training exemplars. Activation of hidden nodes depends on the similarity between the exemplar represented by a node and the external stimulus. The functional role of attention in this model is to increase or decrease the importance of individual dimensions for the calculation of the similarity between an exemplar and a stimulus. For each of the present experiments, ALCOVE predicts that training of the initial discrimination will result in Dimension A, Dimension B, and the contexts receiving the same amount of (high) attention. Thus, the model is also unable to anticipate the context-specific changes in attention indicated by the results from each of the present experiments.

The assumption that attention to a stimulus may vary according to the context in which it appears was put forward by Sutherland and Mackintosh (1971), and a formal versions of this idea can be found, for instance, in Kruschke’s (2001) EXIT model. In the model, attention to a stimulus is mediated by exemplar nodes encoding specific stimulus configurations. Thus, in the model, it is possible that a stimulus receives different amounts of attention depending on other accompanying stimuli. However, in its current form, EXIT does not provide an entirely satisfactory account of the present results. For the process of learning stimulus–outcome associations, the model adopts a purely elemental view of stimulus representation, which makes it impossible for the model to account for the acquisition of the conditional discrimination from Experiment 1. Also, the model assumes that changes in attention occur at the level of individual cues. Changes in attention may generalize to other, similar cues, but the rules governing the generalization of attention are not specified. Therefore, it remains unclear whether the model is able to account for the results from the transfer stages of the present experiments.

The present study is consistent with the general assumption that more attention is paid to stimuli that

reliably signal upcoming events than to unreliable signals. A different relationship between prediction value and attention was proposed by Pearce and Hall (1980). They suggested that stimuli that are followed by unexpected events receive more attention, in order to facilitate further learning about these stimuli. The present results are not in accord with this proposition, but, for other learning situations, it was found that changes in attention did follow Pearce and Hall's principles (see, e.g., Hogarth, Dickinson, Austin, Brown, & Duka, 2008; Kaye & Pearce, 1984). Future research may investigate whether changes in attention according to Pearce and Hall can also come under the control of contextual stimuli.

Compliance with ethical standards

Author note The research reported in this article was supported by the German Research Foundation (DFG) through Grant UE 155/1-2 and Grant SFB/TRR 135, TP B04, to M.U. and H.L., respectively.

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