

**Defining Stimulus Representation in Stimulus-Response Associations Formed on  
the Basis of Task Execution and Verbal Codes**

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**Abstract**

Responding to stimuli leads to the formation of stimulus-response (S-R) associations that allow stimuli to subsequently automatically trigger associated responses. A recent study has shown that S-R associations are not only established by active task execution, but also by the simultaneous presentation of stimuli and verbal codes denoting responses in the absence of own action (Pfeuffer, Moutsopoulou, Pfister, Waszak, & Kiesel, 2017). Here, we used an item-specific priming paradigm to investigate whether the stimulus part of S-R associations formed based on task execution and verbal codes is represented in abstract or specific format by examining whether S-R associations are retrieved for perceptually different forms of the same stimulus or not. Between the prime and probe instance of a stimulus, its format switched from image to word or vice versa. We found that, irrespective of whether stimuli were primed by task execution or verbal coding, performance was impaired when S-R mappings switched rather than repeated between the prime and probe instance of a stimulus. The finding that prime S-R mappings affected probe performance even when stimulus format switched indicates that stimuli were represented in abstract form in S-R association based on both task execution and verbal coding. Furthermore, we found no performance benefits for stimuli primed and probed in the same format rather than different formats, suggesting that stimuli were not additionally represented in specific format. Overall, our findings demonstrate the adaptability of automatized behaviors and indicate that abstract stimulus representations allow S-R associations to generalize across perceptually different stimulus formats.

*Keywords:* Stimulus-response associations; associative learning; verbal codes; automaticity; stimulus representation; abstract; generalization

## Introduction

In everyday life, we sometimes find that we perform behavior patterns, which we have previously executed multiple times, *without conscious thought* and at times even contrary to our current intentions. For instance, driving the same way to work every day, we might sometimes find ourselves in front of our workplace, when in fact we wanted to go to the supermarket. This behavioral automaticity is enabled by stimulus-response (S-R) associations established through the repeated (e.g., Dennis & Schmidt, 2003; Dobbins, Schnyer, Verfaellie, & Schacter, 2004; Logan, 1988, 1990) or one time (e.g., Horner & Henson, 2009; Hsu & Waszak, 2012; Moutsopoulou, Yang, Desantis, & Waszak, 2015; Waszak, 2010; Waszak, Hommel, & Allport, 2003) co-occurrence of stimuli and responses. Even though automatized behavior might sometimes interfere with current intentions (e.g., Horner & Henson, 2011, 2012), they are often beneficial. As S-R associations allow stimuli to automatically trigger associated responses without a need for cognitive processing, cognitive resources are saved for the processing of and acting upon newly-encountered stimuli and S-R contingent responses are speeded up (repetition priming; e.g., Henson, Eckstein, Waszak, Frings, & Horner, 2014; Hommel, 1998; Logan, 1990)

Recently, it has been shown that automatized behavior is much more adaptive than previously thought, as S-R associations have been demonstrated to consist of at least two independent components: Stimulus-Action (S-A) associations between stimuli and motor outputs and Stimulus-Classification (S-C) associations between stimuli and their task-specific classifications (e.g., Horner & Henson, 2009; Moutsopoulou et al., 2015; Pfeuffer, Moutsopoulou, Pfister, Waszak, & Kiesel, 2017). That is, a stimulus, for instance, the image of an apple becomes not only associated with the action of pressing the left or right key in response to it (S-A association), but also with a task-specific classification, for instance, as “small” (S-C association), that is applied to it. This

dissociation between an action and a classification component of S-R associations allows for the independent retrieval of task-specific stimulus classifications and actions.

Furthermore, recent studies have demonstrated that S-R components can be established in the absence of action, that is, without having previously performed responses on the respective stimuli (Pfeuffer et al., 2017). When participants had viewed stimuli while listening to verbally presented information denoting classification and action (verbal codes; e.g., participants viewed the image of an apple and heard the verbal codes “small, right” via headphones), their later responses to the same stimuli were influenced by the previously heard verbal codes. Importantly, though the behavioral effects of verbally coded associations were smaller than for S-R associations based on task execution, both S-A and S-C components established by task execution and by verbal coding were formed after a single pairing of stimulus and response (Pfeuffer et al., 2017). This finding indicates that automatized behaviors can be established fast and without requiring actual responding.

Here, we aimed to extend previous studies by further investigating the flexibility of automatic behaviors. That is, for S-R associations formed on the basis of own action and verbal codes (i.e., in the absence of own action), we investigated whether the stimulus part of the respective S-R associations was coded in abstract representational format (i.e., devoid of specific perceptual features) instead of in a visually specific representational format (i.e., a purely perceptual representation). Furthermore, we examined whether this applied to the stimulus part of both S-A and S-C associations.

If within the stimulus part of S-R associations, stimuli (e.g., a small red car) were coded in specific format, only the exact same visual stimulus (i.e., the same exemplar) would subsequently be able to automatically trigger the associated response. However, if stimuli were coded and integrated in S-R associations in an abstract format, responses should subsequently be automatically triggered for various exemplars of the same

stimulus (i.e., different pictures of cars) or when the stimulus is presented in a different representational format (i.e., the word “car” written out rather than the picture of a car).

Empirical findings regarding the representational format of the stimulus part of S-R associations are controversial. A study by Schnyer, Dobbins, Nicholls, Davis, Verfaellie, and Schacter (2007) suggested that the stimulus part of S-R associations is coded in a specific visual format, because priming effects did not transfer from one stimulus exemplar to another. In this study, participants classified objects according to their size relative to a shoe box. Stimuli were paired with the same S-R mapping three times during a prime phase. In a subsequent probe phase the response mapping for these stimuli was either repeated or reversed. Crucially, during the probe phase, some stimuli re-appeared as exactly the same exemplar (e.g., the same image of a car), whereas other stimuli were substituted by a visually different exemplar (i.e., the image of another object associated with the same object name; e.g., the image of another car). In this setting, priming effects (evidenced by faster reaction times at test for repetitions in response mapping in comparison to reversals) only occurred when the same exemplar was presented in prime and probe, but not when exemplars differed.

However, several subsequent experiments suggested that the stimulus part of S-R associations, is coded in an abstract representational format (Denkinger & Koutstaal, 2009; Horner & Henson, 2011, 2012). For instance, Horner and Henson (2011) used an item-specific priming paradigm, in which stimuli were presented as object names during primes and as object images during probes (or vice versa). They compared this across-format condition with a within-format condition, in which objects were primed and probed in the same format (within-format; i.e., objects consistently appeared either as object names or object images in prime and probe). Participants classified the size of objects (presented in word or image format) in relation to one of two size referents. For instance, they were asked whether an object was bigger than a shoebox and indicated

their answer by pressing a yes or no key. Between the prime and probe instance of an object, the size referent could remain the same or change. Thus, the required response could either repeat or switch between prime and probe. During probes, participants were faster at classifying object size when the required response repeated rather than switched. This pattern of results was observed for both stimuli that were probed within- and across-format.

Additionally, participants' neural activation, assessed via EEG and fMRI, was sensitive to item-specific repetitions and switches of response even when stimulus format changed between prime and probe (Horner & Henson, 2012). These findings suggest that priming effects occurred for stimuli tested in a different visual format, indicating that S-R associations formed for object names affected later performance for the corresponding object images (and vice versa) and allowed the same stimulus, presented in a visually different format (across-format), to automatically trigger the action previously bound to it. Thus, the findings of Horner and Henson (2011) imply an abstract instead of perceptually specific representation of the stimulus part of S-R associations. However, priming effects were shown to be more pronounced when stimulus format repeated (within-format), suggesting that a perceptually specific stimulus representation was additionally bound to the response (Horner & Henson, 2011). In addition, a recent study showed that changing the perceptual features of stimuli (e.g., colour) from prime to probe, did not affect either S-C or S-A retrieval, further supporting the theory that the representation of the stimulus incorporated in an S-R link is not at the perceptual level (Allenmark et al., 2015)

Importantly, there is a crucial difference between the study of Schnyer et al. (2007) and the studies of Denkinger and Koutstaal (2009) and Horner and Henson (2011, 2012) that might have contributed to diverging results. In Schnyer et al.'s study that did not find any indication of abstract stimulus representations for S-A associations, S-A

associations were assessed unconfounded by S-C associations. In contrast, in Denkinger and Koutstaal's and Horner and Henson's studies, switches in action mapping coincided with switches in classification mapping. Thus, S-A and S-C associations could not be separated. In these studies, it is therefore unclear whether across-format effects relied on abstract stimulus representations within S-A and/or S-C associations. Horner and Henson observed that priming effects were more pronounced when stimulus format repeated rather than switched. They therefore assumed both perceptually specific and abstract stimulus representations within S-R associations. However, S-A and S-C mappings were confounded in their study. Therefore, their findings could also indicate that in either S-A or S-C associations, stimuli might have been represented perceptually specifically, whereas they were represented in abstract form in the respective other S-R component. Assuming that studies using different stimulus exemplars and studies using different stimulus formats are comparable, this might suggest that only stimuli within S-C, but not S-A associations are represented in abstract form.

Allenmark et al. (2015) provided evidence that both S-A and S-C associations were retrieved when stimuli changed in three basic visual features between a prime and a probe instance and thus proposed that retrieval of S-C and S-A associations does not depend on representation of stimuli at the perceptual level. Yet, in comparison to the studies by Schnyer et al. (2007) and Horner and Henson (2011, 2012), Allenmark et al. (2015) changed basic visual stimulus features (colour, motion direction and disparity) maintaining form as a constant feature between between prime and probe, rather than changing the entire visual representation of the object. Thus, it is arguable whether their results can be interpreted as solid evidence for abstract stimulus representations.

Here, we aimed to investigate whether stimuli incorporated in S-A and S-C associations were represented in a specific or abstract format more closely. Like

Allenmark et al. (2015) and Moutsopoulou et al. (2015) we varied S-A and S-C mappings orthogonally. To assess the perceptual specificity of the stimulus part of S-A and S-C associations, we varied stimulus format between image and word to ensure that there was no perceptual overlap between prime and probe stimulus presentation (e.g., from repeating stimulus features when switching exemplars). Moreover, we assessed whether stimulus format was the same for S-R associations formed based on task execution and based on verbal coding by adapting a recent experiment by Pfeuffer et al. (2017).

In their study, Pfeuffer et al. (2017) used an item-specific priming paradigm and participants classified images of everyday objects either according to their size or mechanism as indicated by a preceding task cue. Participants indicated the correct classification by pressing a left or right key. Each stimulus was only presented twice, once as a prime and, with a delay of several trials, once as a probe. Between the prime and probe instance of a stimulus, the to-be-performed classification (size vs. mechanism) as well as the correct action (left vs. right key press to indicate classification) independently repeated or switched leading to independent repetitions or switches in S-A and S-C mapping between the prime and probe instance of a stimulus. The authors found that both when participants had actively classified stimuli during prime trials by pressing a key (i.e., executed blocks) and when participants had attended to verbal codes denoting class and action (e.g., “small, right!”) without themselves performing any action upon stimuli (i.e., verbally coded blocks), reaction times (RTs) and error rates (PEs, percentages of errors) were increased when S-A or S-C mappings switched rather than repeated. This finding indicates that independent S-A and S-C associations had been formed during primes and were retrieved during probes.

To investigate the stimulus format of executed and verbally coded S-A and S-C associations, we adapted the paradigm of Pfeuffer et al. (2017, Experiment 1) by



varying stimulus format between the prime and probe instance of a stimulus from object image to object name or vice versa (see also Horner & Henson, 2011, 2012). That is, prime stimuli were words denoting everyday objects (e.g., “car”) and probe stimuli were the corresponding object images (e.g., the picture of a car) or vice versa. We hypothesized that both the stimulus part of S-A and S-C associations is coded in abstract representational format, thus allowing priming effects to transfer between stimulus formats, that is, from word to image and vice versa. Furthermore, we aimed to investigate possible differences between the representational format of the stimulus part of S-R associations formed based on active task execution and listening to verbal codes.

### **Experiment 1**

Experiment 1 used an item-specific priming paradigm to investigate whether the representation of the stimulus part of S-A and S-C associations established based on task execution and verbal coding was specific or abstract. Each stimulus appeared twice throughout the experiment. Stimuli appeared once as a prime and once as a probe and each stimulus was primed in one format (image vs. word) and probed in the other.

### **Methods**

**Participants.** Forty participants (14 male, 3 left handed; mean age = 24.3 years, SD = 4.1) took part and provided written informed consent prior to their participation. Sample size was determined according to the effect size reported in a previous study investigating item-specific priming by execution and verbal codes (Pfeuffer et al., 2017). The data of one participant who committed errors on more than 30% of the probe trials was excluded from analyses.

**Stimuli and apparatus.** Participants sat approximately 60 cm from a 24” LCD screen (1920 pixels x 1080 pixels) in a dimly lit, sound attenuated room. They wore headphones throughout the experiment and the index fingers of their left and right

hands rested on two external keys placed in front of them to the left and right (key distance 13.5 cm).

Based on the object images used in a prior study (Pfeuffer et al., 2017; adapted from a set by Brady, Konkle, Alvarez, & Oliva, 2008, and Moutsopoulou et al., 2015; image size 256 pixels x 256 pixels), we generated 512 corresponding object names. Objects (images and names) were chosen so that the respective objects were easy to classify according to size (small vs. large) and mechanism (mechanical vs. non-mechanical). Of the original 512 object images, 128 fell into each of the four possible size-mechanism category combinations (small mechanical, small non-mechanical, large mechanical, large non-mechanical). Three raters were presented with the newly-generated object names and judged the size and mechanicity of the named objects. Only objects for which all three raters agreed on a size and mechanism classification based on the object name were used in the study. In order to achieve a full set of 512 object images and corresponding object names, additional word stimuli (i.e., object names) were created and corresponding object images were added to complete the set. The image and name of each of these new objects were again rated by three raters and only objects for which the raters agreed on a size and mechanism classification were added. Objects for which the raters did not agree were excluded and new objects of the same size and mechanism category were added until we reached a set of 512 object images and corresponding object names. Due to our focus on the ease of classification, word length could not be matched. The final target stimulus set consisted of 128 objects (names and corresponding images) of each size-mechanism category combination (small mechanical, small non-mechanical, large mechanical, large non-mechanical). Sixteen additional objects (names and images) were used in a preceding practice of the task.

Task-specific cues indicated whether participants were to perform a size or mechanism classification on objects. The task cue for the size task was either “K + G”

or “G + K”, corresponding to the first letter of the German words for “small” (“klein”) and “large” (“groß”). The mechanism task was cued accordingly with either “M + N” or “N + M” for “mechanical” (“mechanisch”), and “non-mechanical” (“nicht-mechanisch”). Objects had to be classified by pressing the response key (left vs. right) that spatially corresponded to the correct object classification. For instance, if the task cue “K + G” was followed by a small object, participants were to press the left key (see Figure 1).

In *verbally coded blocks’ prime trials*, verbal codes regarding class and action were presented via voice recording playbacks (1.8 - 2.3 s). Recordings first informed participants about the class and then about the action associated with an object (e.g., “klein, rechts”, Eng.: “small, right”). All verbal code recordings featured an emotionally neutral, female voice.

**Design and procedure.** After eight initial practice blocks (4 executed, 4 verbally coded), the main experiment consisting of 128 blocks (64 executed, 64 verbally coded) ensued. This resulted in 1024 trials total (512 prime trials and 512 probe trials) and 32 trials per condition during probes. Executed and verbally coded blocks appeared in random sequence and participants were informed about the prime type of the following block prior to its beginning. Each block consisted of eight trials, four prime trials followed by four probe trials. For each block, four new objects were chosen as targets and presented once as a prime and once as a probe (lag 2-7 trials, see Figure 1). Thus, each object only appeared twice throughout the experiment.

Between the prime and probe instance of an object, stimulus format (word vs. image) always switched. That is, in each block all four objects were either primed in word format and probed in image format or vice versa (prime-probe format: image-word vs. word-image). Both prime-probe formats occurred equally often during executed and verbally coded blocks. The prime-probe format remained the same for all

four primed objects of a block before switching for the probe instances of the respective objects.

In executed blocks, each trial started with a task cue presented for 700 ms and was followed by the target that disappeared upon responding (maximum duration 2000 ms). A feedback screen (500 ms) ensued and informed participants about the accuracy of their classification response (“Richtig!”, Eng.: “correct!” vs. “Fehler!”, Eng.: “error!”). In case no response was provided within 2000 ms, the feedback message “zu langsam!” (Eng.: “too slow!”) indicated that participants should speed up their responses.

Verbally coded probe trials were equivalent to executed probe trials. In verbally coded prime trials, however, participants did not actively classify objects, but merely attended to verbal codes denoting class and action. Objects were initially presented for 700 ms and remained on screen for additional 3000 ms while verbal codes were presented via headphones. Participants were instructed not to perform any actions during verbally coded prime trials, but to attend to the presented verbal codes and try to memorize them. They were additionally told to position their fingers on the keys at the beginning of a block irrespective of its type to be ready to respond as fast as possible when required.

---- INSERT Figure 1 about here ----

Crucially, between the prime and probe instance of a specific item, the S-A and S-C mappings repeated or switched independently so that four switch conditions were possible (full repetition, action switch, classification switch, full switch; see Figure 2). Each switch condition was equally frequent for all four combinations of prime type (executed vs. verbally coded) and prime-probe format (image-word vs. word-image). Switch conditions were randomly allocated to objects across the entire experiment so that the mapping during the prime instance of an object did not allow predictions about the mapping in its later probe instance. That is, each object’s switch condition was

drawn from a pool of all switch conditions for a block type. As such, participants could not anticipate the classifications or actions they would have to perform upon stimuli during probes.

---- INSERT Figure 2 about here ----

Finally, in order to ensure and assess participants' attention to prime instances, we asked our participants to try to memorize prime trial S-A and S-C mappings. That is, either the verbal codes denoting class and action presented during verbally coded prime trials or participants' self-performed classifications and actions during executed prime trials. At the end of each block, one of the objects was randomly chosen and participants had to report the class ("Kategorie?", Eng.: "category?"; press "K" for "klein"/"small", "G" for "groß"/"large", "M" for "mechanisch"/"mechanic", and "N" for "nicht-mechanisch"/"non-mechanic") and action ("Reaktion R/L?", Eng.: "reaction R/L?"; press left/right key) mapped to this item during its prime instance by pressing a corresponding key. This memory recall trial was not speeded and participants were instructed to focus on high accuracy.

## **Results**

We excluded the first probe trial of each block to account for possible influences of the switch from mere listening to active classification that occurred in verbally coded blocks, but not in executed blocks. Moreover, trials with response omissions in primes (1.5%) and/or corresponding probes (1.0%) and probe trials with errors in corresponding primes (15.4%) were excluded from all analyses. Prime trials with erroneous responses and the corresponding probe trials were excluded from analyses as for these trials participants could have formed associations with incorrect actions and/or classifications. For RT analyses, probe trials with erroneous responses (14.1%) were additionally excluded. Furthermore, verbally coded prime trials with accidental responses and their corresponding probes (0.3%) were excluded, as participants could

have formed S-R associations on the basis of own action on these trials. On average, 21.9% of probe trials were excluded from the probe trial RT analyses.<sup>1</sup>

Finally, RTs deviating from their individual cell means by 3 standard deviations or more were counted as outliers and discarded (prime: 0.5%, probe: 0.3%). Prime trial RT and error rate (PE, percentage of errors) analyses revealed that object images were classified faster and more accurately than object names (see Appendix). Apart from this main effect, there were no significant a priori differences between conditions. Detailed analyses of prime trials and memory recall trials can be found in the Appendix. In the following, we focus on the critical probe trial results (see Figure 3).

**Probe RT analyses.** Probe trial RTs were submitted to a 2 x 2 x 2 x 2 repeated measures analysis of variance (ANOVA) with the within-subject factors prime type (executed vs. verbally coded), prime-probe format (image-word vs. word-image), classification (repetition vs. switch), and action (repetition vs. switch). Classification and action switches were defined as item-specific changes in S-C and S-A mapping between the prime and probe instance of an object.

Participants were significantly faster at classifying objects (both objects primed in image and word format) during verbally coded blocks in comparison to executed blocks,  $F(1,38) = 17.96, p < .001, \eta_p^2 = .32$  (see Figure 3). Moreover, participants were

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<sup>1</sup> Please note that the percentage of excluded probe trials is not the summation of the previously mentioned percentages of excluded trials, as several exclusion criteria can apply to one probe trial. For instance, participants could have responded incorrectly during both prime and corresponding probe. Probe trials with erroneous responses or response omissions during primes are commonly excluded in item-specific priming studies, as it cannot be determined which associations participants might have formed during such prime trials.

significantly faster at classifying object images (prime-probe format: word-image) than at classifying object names (prime-probe format: image-word),  $F(1,38) = 96.55, p < .001, \eta_p^2 = .72$ . Classification switches were associated with prolonged RTs in comparison to classification repetitions,  $F(1,38) = 37.19, p < .001, \eta_p^2 = .50$ , whereas RTs did not significantly differ between action switches and action repetitions,  $F < 1$ . Furthermore, prime type and classification significantly interacted,  $F(1,38) = 11.86, p = .001, \eta_p^2 = .24$ , indicating that differences regarding classification switches and repetitions were larger for executed than verbally coded primes. Yet, switches in S-C mapping were associated with significantly longer RTs in comparison to classification repetitions in both executed blocks,  $t(38) = 6.76, p < .001, d = 1.08$ , and verbally coded blocks,  $t(38) = 2.26, p = .030, d = 0.36$ . All other interactions failed to reach significance,  $F_s \leq 2.61, p_s \geq .115, \eta_p^2 \leq .06$ .

---- INSERT Figure 3 about here ----

**Probe PE analyses.** A  $2 \times 2 \times 2 \times 2$  repeated measures ANOVA on PEs with the within-subjects factors prime-probe format, prime type, classification, and action showed that participants committed more errors when classifying object names (prime-probe format: image-word) than when classifying images (prime-probe format: word-image),  $F(1,38) = 13.41, p = .001, \eta_p^2 = .26$ . Moreover, both switches in classification mapping,  $F(1,38) = 49.31, p < .001, \eta_p^2 = .57$ , and switches in action mapping,  $F(1,38) = 7.49, p = .009, \eta_p^2 = .17$ , were associated with significant PE increases relative to repetitions. Furthermore, prime type and prime-probe format significantly interacted,  $F(1,38) = 4.61, p = .038, \eta_p^2 = .11$ . PEs were significantly larger for object names (prime-probe format: image-word) than object images (prime-probe format: word-image) in verbally coded blocks,  $t(38) = 4.54, p < .001, d = 0.73$ , but did not significantly differ in executed blocks,  $t(38) = 0.99, p = .326, d = 0.16$ . Prime type and classification showed a non-significant trend towards an interaction,  $F(1,38) = 3.99, p =$

.053,  $\eta_p^2 = .10$ . Post-hoc paired t-tests showed that classification switches were associated with increased PEs in comparison to classification repetitions in both executed,  $t(38) = 6.60, p < .001, d = 1.06$ , and verbally coded blocks,  $t(38) = 2.85, p = .007, d = 0.46$ . Furthermore, classification and action showed a tendency to interact,  $F(1,38) = 3.62, p = .065, \eta_p^2 = .09$ , with the effect of action switches tending to be larger for classification repetitions rather than classification switches. Finally, the three-way interaction between prime type, classification, and action showed a non-significant trend,  $F(1,38) = 3.23, p = .080, \eta_p^2 = .08$ , with the interaction of classification and action descriptively being more pronounced for stimuli primed in word format than in image format. All other effects failed to approach significance,  $F_s \leq 1.45, p_s \geq .236, \eta_p^2 \leq .04$ .

## Discussion

In Experiment 1, we used an item-specific priming paradigm adapted from Pfeuffer et al. (2017) to investigate whether the stimulus part of executed and verbally coded S-A and S-C associations, is represented in specific or abstract format. During a prime instance, stimuli were primed in one stimulus format (image vs. word) either by active classification (i.e., task execution), or by attending to verbally presented codes denoting class and action (i.e., verbally coded). Between the prime instance of a stimulus and its later item-specific probe instance stimulus format switched (i.e., from image to word or vice versa) and S-A and/or S-C mapping repeated or switched independently.

We found significant RT and PE increases for classification switches in comparison to classification repetitions, indicating that participants indeed had formed S-C associations during primes which they automatically retrieved during probes. Prime S-C mappings affected probe performance even though stimulus format changed between the prime and probe instance of a stimulus, indicating that participants had represented



the stimulus part of the S-C association in an abstract format rather than in a visually specific format.

S-C associations were established during primes and affected probe performance both when participants had actively classified objects during primes and when participants had merely listened to verbal codes during primes. However, in line with prior findings (Pfeuffer et al., 2017) we found priming effects in RTs to be less pronounced for verbally coded S-C mappings in comparison to executed S-C mappings. Error rates showed a non-significant tendency in the same direction, overall suggesting that, although executed and verbally coded S-C associations are similar in structure, they differ in their behavioral impact.

Interestingly, contrary to Pfeuffer et al. (2017) we found no indication of priming effects due to prime trial S-A mappings in probe trial RTs. In contrast to the across-format priming effects investigated here, Pfeuffer et al. (2017) had investigated within-format priming effects. Thus, this finding may be taken as evidence against an abstract representation of stimuli within S-A associations. Yet, our error rates results indicated comparable across-format priming effects. Probe trial PEs were significantly increased when action mappings switched rather than repeated between the prime and probe instance of a stimulus irrespective of the type of priming (task execution vs. verbal coding) used on the stimulus. There are several possible interpretations for this pattern of RT and error rate results. First, prior studies have demonstrated that S-A effects are substantially smaller than S-C effects and S-A associations are therefore less reliably found (e.g., Hsu & Waszak, 2012; Moutsopoulou et al., 2015; Pfeuffer et al., 2017). Thus, our failure to find significant S-A effects in RTs might just reflect the small size of S-A effects and we could therefore interpret the observed priming effect in PEs as evidence for an abstract representation of the stimulus part of S-A associations. Interestingly, prior studies that found evidence for an abstract representation of stimuli

in S-R associations had confounded S-A and S-C mappings (Denkinger & Koutstaal, 2009; Horner & Henson, 2011, 2012). That is, switches in S-A mapping were always simultaneously associated with switches in S-C mapping (and size referent changes), whereas S-A mapping repetitions were always associated with S-C mapping repetitions. Thus, significant priming effects in these studies might have been boosted by S-C mappings, explaining why we found rather weak evidence for S-A priming effects for S-A mappings alone. Thus, although our findings regarding S-A associations are not unequivocal, our error rate results are the first evidence suggesting that the stimulus part of S-A associations (unconfounded with S-C mappings) is coded in an abstract representational format as is the stimulus part of S-C associations.

Still, our PE results provided evidence for an abstract representation of stimuli within S-A associations and thus contradict the findings of Schnyer et al. (2007), who did not observe priming effects across exemplars for switches and repetitions in S-A mappings that were not confounded with S-C mappings. Although Denkinger and Koutstaal (2009) also used different stimulus exemplars and found evidence for an abstract coding of stimuli within S-R associations, they had confounded S-A and S-C associations. Thus, their findings cannot serve as evidence contrary to the findings of Schnyer et al. (2007). Yet, possibly, the absence of significant S-A priming effects in the study of Schnyer et al. (2007) can also be attributed to the small effect size of S-A priming effects in general. Further studies that independently investigate the representational format of stimuli within S-A and S-C associations will be necessary to determine whether stimuli within S-A associations are truly represented in abstract format.

Finally, Experiment 1 did not allow us to investigate whether the stimulus part of S-R associations was represented in specific format in addition to abstract format, as suggested by Horner and Henson (2011). In order to address this question, we

conducted Experiment 2 in which stimuli were primed and probed in word format. Thus, comparing the data of Experiment 2 (words in prime and probe) to Experiment 1 (word-image vs. image-word) and the data of Experiment 1 of Pfeuffer et al. (2017) on object images (images in prime and probe) allowed us to investigate whether priming effects were increased when stimulus format repeated between prime and probe (i.e., test within-format) in comparison to when stimulus format switched (i.e., test across-format). Such a pattern of results would indicate an additional specific representation of stimuli within S-R associations or two separate S-R associations, one in which the stimulus part is represented abstractly and one in which its representation is perceptually specific.

### **Experiment 2**

Experiment 2 investigated executed and verbally coded S-A and S-C associations for stimuli primed and probed in word format (i.e., object names) in order to compare stimuli primed and probed within-format (word stimuli: Experiment 2; image stimuli: Pfeuffer et al., 2017) and across-format (Experiment 1). This allowed us to assess whether the stimulus part of S-R associations formed on the basis of active task execution and merely listening to verbal codes was represented at a perceptually specific level in addition to at an abstract level (or whether two separate S-R associations incorporating abstract and specific stimulus representations, respectively, were formed). As a previous study using word stimuli to examine executed associations found evidence for S-C associations, but not S-A associations (Hsu & Waszak, 2012), we also used Experiment 2 to assess whether the absence of S-A effects in RTs in Experiment 1 could be attributed to the word stimuli.

### **Methods**

**Participants.** Forty participants (7 male, 4 left handed; mean age = 24.6 years, SD = 4.2) took part and provided written informed consent prior to their participation. We

excluded data of one participant, because his error rate exceeded 30% during probe trials. Data of another participant were excluded, because she loudly rehearsed the verbal codes throughout the experiment. Two new participants were recruited so that the final sample contained 40 participants.

**Stimuli and apparatus.** Experiment 2 featured the same task cues and largely the same object names as Experiment 1. We considered participants' overall percentage of correct responses during primes for each object name in Experiment 1 and excluded object names that were responded to incorrectly on at least 50% of the trials. Then, the same iterative process as in Experiment 1 was used to generate new object names until we reached a full set of 512 stimuli.

**Design and procedure.** The procedure of Experiment 2 was equivalent to Experiment 1 except that stimulus format did not switch between the prime and probe instance of a stimulus. Stimuli were consistently presented in word format.

## Results

For probe trial analysis, the first probe trial of each block was excluded. Trials with response omissions (prime: 1.6%, probe: 1.3%) were excluded from all analyses and probe trials with commission or omission errors in corresponding prime trials were excluded from probe analyses. Furthermore, trials with accidental responses during verbally coded prime trials (0.6%) as well as their corresponding probes were excluded. Finally, all trials with errors (prime: 15.5%, probe: 13.3%) were excluded from RT analyses. Due to these restrictions, on average 21.5% of probe trials were excluded from the probe trial RT analyses.

Additionally, outliers, that is, RTs deviating from their corresponding cell mean by 3 standard deviations or more, calculated separately for participants and conditions, were removed from RT analyses (prime: 0.8%, probe: 0.8%). Prime trial analyses revealed that probe results were not compromised by a priori differences between

conditions. Information on prime trial and memory recall results can be found in the Appendix. In the following, we focus on the critical probe trial results (see Figure 4). We first analyze the data of Experiment 2 in isolation. Then we compare the results of this Experiment (within-format probing for word stimuli) with the results of Experiment 1 (across-format probing for word and image stimuli) and the data of Pfeuffer et al. (2017; within-format probing for image stimuli).

**Probe RT analyses.** Probe trial RTs were submitted to a 2 x 2 x 2 repeated measures ANOVA with the within-subject factors prime type (executed vs. verbally coded), classification (repetition vs. switch), and action (repetition vs. switch). Participants responded slower in executed blocks in comparison to verbally coded blocks,  $F(1,39) = 5.39, p = .026, \eta_p^2 = .12$ . Moreover, participants were significantly faster when classification repeated rather than switched,  $F(1,39) = 25.37, p < .001, \eta_p^2 = .39$  (see Figure 4). This effect was larger in executed than in verbally coded blocks,  $F(1,39) = 5.03, p = .031, \eta_p^2 = .11$ . Nevertheless, classification switches were associated with significantly higher RTs than classification repetitions in both executed blocks,  $t(39) = 5.23, p < .001, d = 0.83$ , and verbally coded blocks,  $t(39) = 2.07, p = .045, d = 0.33$ . The main effect of action did not reach significance,  $F < 1$ . Yet, prime type significantly interacted with action,  $F(1,39) = 5.45, p = .025, \eta_p^2 = .12$ . Action switches were associated with significantly increased RTs in comparison to action repetitions in executed blocks,  $t(39) = 2.53, p = .015, d = 0.40$ , but RTs did not significantly differ between action switches and action repetitions in verbally coded blocks,  $t(39) = 1.32, p = .195, d = 0.21$ . The interaction between classification and action and the three-way interaction failed to reach significance,  $F_s < 1$ .

---- INSERT Figure 4 about here ----

**Probe PE analyses.** Parallel to the analysis on RTs, probe PEs were subjected to a 2 x 2 x 2 repeated measures ANOVA with the within-subject factors prime type,

classification, and action. The main effect of prime type showed a non-significant trend towards larger error rates in verbally coded blocks as compared to executed blocks,  $F(1,39) = 3.32, p = .076, \eta_p^2 = .08$  (see Figure 4). Classification switches were associated with significantly higher PEs than classification repetitions,  $F(1,39) = 30.17, p < .001, \eta_p^2 = .44$ . Again, prime type and classification interacted,  $F(1,39) = 29.84, p < .001, \eta_p^2 = .43$ . Classification switches were associated with higher PEs as compared to classification repetitions in executed blocks,  $t(39) = 7.63, p < .001, d = 1.21$ , but not in verbally coded blocks,  $t(39) = 0.24, p = .813, d = 0.04$ . All other effects failed to reach significance,  $F_s \leq 2.74, p_s \geq .106, \eta_p^2 \leq .07$ .

**Cross-experiment comparison of switch costs.** In order to investigate whether stimuli were coded in specific representational format in addition to abstract format, we compared S-A and S-C switch costs ( $\Delta RT = RT_{\text{switch}} - RT_{\text{repetition}}$ ) in Experiment 1 (40 participants, 14 male, 3 left handed, mean age = 24.3 years; mean RT probe words = 945 ms, mean PE probe words = 15.4%, mean RT probe images = 884 ms, mean PE probe images = 12.9%), in which stimulus format switched between the prime and probe instance of a stimulus, to Experiment 2 (word format; 40 participants, 7 male, 4 left handed; mean age = 24.6 years; mean RT probe words = 858 ms, mean PE probe words = 13.3%) and the data of Pfeuffer et al. (2017; Experiment 1, image format; 40 participants, 10 male, 3 left handed, mean age = 23.0 years; mean RT probe images = 719 ms, mean PE probe images = 10.2%). In all three experiments, participants consisted partly of Psychology students who took part for course credit and partly of participants taking part for monetary compensation. We conducted a 2 x 2 x 2 mixed-design ANOVA with the between-subject factor of format consistency (same vs.

different) and the within-subject factors of switch type (classification vs. action) and prime type (executed vs. verbally coded) on RT and PE switch costs (see Table 1).<sup>2</sup>

In this analysis, neither the main effect of format consistency,  $F(1,117) = 1.39, p = .241, \eta_p^2 = .01$ , nor any of the interactions with format consistency,  $F_s < 1$ , reached significance. As expected based on previous analyses, participants' RT switch costs for switches in S-C mapping were significantly larger than for switches in S-A mapping,  $F(1,117) = 35.40, p < .001, \eta_p^2 = .23$ . Additionally, RT switch costs were more pronounced in executed blocks in comparison to verbally coded blocks,  $F(1,117) = 23.54, p < .001, \eta_p^2 = .17$ . Switch type and prime type significantly interacted,  $F(1,117) = 6.94, p = .010, \eta_p^2 = .06$ , as RT switch cost between executed and verbally coded blocks significantly differed for classification switch costs,  $t(118) = 5.98, p < .001, d = 0.55$ , but not action switch costs,  $t(118) = 1.82, p = .072, d = 0.17$ .

PE switch costs showed the same pattern. Neither the main effect of format consistency,  $F(1,117) = 1.39, p = .241, \eta_p^2 = .01$ , nor any of the interactions with format consistency,  $F_s < 1$ , reached significance. PE classification switch costs were significantly larger than PE action switch costs,  $F(1,117) = 29.72, p < .001, \eta_p^2 = .20$ . Furthermore, PE switch costs were larger in executed blocks than in verbally coded

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<sup>2</sup> Please note that the stimulus sets in the experiments differed partly. Additionally, mean probe RTs (and PEs) differed between the three experiments. For both stimuli probed in word and image format, RTs in Experiment 1, in which stimulus format changed between prime and probe, were larger than in Experiment 2 and the study of Pfeuffer et al. (2017), respectively. As some priming effects increase in size with increasing RTs, differences in the size of S-A and S-C switch costs between stimuli probed in the same versus a different format might thus have been overshadowed by the overall difference in RTs.

blocks,  $F(1,117) = 24.60, p < .001, \eta_p^2 = .17$ . Switch type and prime type interacted,  $F(1,117) = 4.45, p = .037, \eta_p^2 = .04$ . Both classification switch costs,  $t(118) = 5.73, p < .001, d = 0.53$ , and action switch costs,  $t(118) = 2.00, p = .048, d = 0.18$ , were significantly larger in executed than in verbally coded blocks.

### **Discussion**

Experiment 2 used an item-specific priming paradigm to investigate whether both S-A and S-C associations could be formed and retrieved for object names like for object images and whether these associations could be established both by task execution and by attending to verbal codes. In prime trials participants either actively classified objects via key presses or attended to verbal codes denoting class and action. Between the prime and probe instance of an object, S-A and/or S-C mapping repeated or switched independently.

Item-specific switches in S-C mapping were associated with significant RT increases relative to repetitions in S-C mapping in both executed and verbally coded blocks, suggesting priming effects from prime trial S-C mappings. Furthermore, error rates were significantly higher for classification switches rather than repetitions in executed blocks, but not in verbally coded blocks. These findings indicate that participants formed S-C associations during prime trials and these S-C associations subsequently affected probe trial performance. Although, priming effects of S-C mappings were significantly more pronounced in executed blocks, S-C associations were apparently formed both by task execution and by verbal codes. Moreover, the reduced behavioral effect of S-C associations established by verbal coding mirrors the findings of a prior study on verbally coded S-R associations with object images (Pfeuffer et al., 2017).

For switches and repetitions of S-A mapping, significant RT differences (i.e., longer RTs for action switches rather than action repetitions) only emerged in executed blocks,



but not in verbally coded blocks. Furthermore, error rates did not indicate any differences between switches and repetitions in S-A mapping. These findings might suggest that, for word stimuli, S-A associations can only be established by task execution and not by verbal coding. However, as mentioned before, previous studies have shown that effects of prior S-A mappings are rather small in comparison to S-C effects (Hsu & Waszak, 2012; Moutsopoulou et al., 2015; Pfeuffer et al., 2017). Therefore, S-A effects are less reliably detected.

Overall, the findings of Experiment 2 affirm our hypothesis that for word stimuli S-A priming effects might be less reliably found than S-C priming effects. With regards to the findings of Experiment 1, this suggests that our failure to find significant priming effects of S-A mappings in RTs does not necessarily reflect that S-A associations are coded in a specific stimulus format. Instead, as our PE results suggested that the stimulus part of S-A associations might also be represented in an abstract format, the absence of RT S-A priming effects in Experiment 1 likely reflects the small size of S-A priming effects. In order to obtain definitive evidence for the abstract coding of the stimulus part of S-A associations, future studies might want to consider using multiple prime instances to create more stable S-A associations and thus increase the chance of observing a transfer of S-A priming effects between stimulus formats in both RTs and PEs.

Finally, a cross-experiment comparison indicated that repetitions and switches in stimulus format between the prime and probe instance of a stimulus did not affect item-specific switch-induced performance costs. Increased switch costs for stimuli primed and probed within-format (image – image, word – word) rather than across-format (image – word, word – image) observed in a prior study (Horner & Henson, 2011) suggested that in addition to their abstract representation, stimuli might also be coded in a specific format. In contrast, a study investigating stimuli that only changed in one

perceptual feature (colour) between their prime and probe instance found no indication of an additional perceptually specific representation of stimuli (Allenmark et al., 2015). Importantly, although our paradigm more closely resembles the paradigm of Horner and Henson (2011), we found no evidence of additional perceptually specific stimulus representations. That is, we did not find a difference in item-specific switch costs for S-A and S-C mappings between stimuli probed within-format and across-format. Our findings therefore replicate the findings of Allenmark et al. (2015) for stimuli changing in basic visual features (colour, motion direction, and disparity) between their prime and probe instance and contradict the findings of Horner and Henson (2011). As, however, the manipulation of Allenmark et al. (2015) is not comparable to the switch between stimulus formats used in Horner and Henson's (2011) study and our study, we cannot consider these findings as conclusive evidence that stimuli are not additionally coded in a perceptually specific format. Further experiments are necessary to provide definite conclusions.

### **General Discussion**

Overall, our results replicate previous findings suggesting that S-R associations can be formed not only by task execution, but also by verbal coding in the absence of action (Pfeuffer et al., 2017). In addition, we demonstrate that both executed and verbally coded S-R associations can affect performance even when stimuli were presented in different representational formats in prime and probe instance (image vs. word). In line with prior studies on executed S-R associations (Horner & Henson, 2011, 2012), these findings indicate that, both when S-R associations were formed by task execution and by verbal coding, stimuli were incorporated in the respective S-R associations in abstract representational format, allowing the same stimuli presented in different formats (image vs. word) to subsequently automatically trigger associated responses.

Moreover, extending previous research, we differentiate between the S-C and S-A component of S-R associations and demonstrate that the stimulus part of both S-C and S-A associations (executed as well as verbally coded) is represented in abstract format. Priming effects (i.e., RT and PE increases for mapping switches as compared to mapping repetitions) of S-C and S-A mappings were not only observed when stimulus format repeated between the prime and probe instance of a stimulus, but also when stimulus format switched from image to word or vice versa between prime and item-specific probe. For S-C mappings, we found substantial priming effects in both probe RTs and PEs even when stimulus format switched between the prime and probe instance of a stimulus. For S-A mappings, we only observed priming effects in probe PEs, but not RTs, when stimulus format switched between the prime and probe instance of a stimulus. Given the small effect size of S-A priming effects in general, we consider this evidence suggestive of an abstract representation of not only the stimulus part of S-C associations, but also the stimulus part of S-A associations. As previous studies investigating the retrieval of S-R associations for stimuli that fully switched perceptual format between prime and probe (Horner & Henson, 2011, 2012) had confounded S-A and S-C associations, this study is the first to provide evidence for the abstract representation of the stimulus part of S-C as well as S-A associations.

Our findings provided evidence for the abstract representation of the stimulus part of S-R associations and did not provide evidence for an additional specific representation of stimuli within S-R associations. However, the conclusion that stimuli within S-R associations are not additionally represented in specific format rests on a null effect in a cross-experiment comparison. For this reason future studies will have to determine whether the stimulus part of S-R associations formed on the basis of task execution and verbal codes is truly only represented in abstract format (in line with

Allenmark et al., 2015), as our findings suggest, or whether it is also represented in specific format (in line with Horner & Henson, 2011).

Importantly, our findings suggest that S-C and S-A associations created by task execution and verbal coding did not differ in terms of the representational format in which stimuli were stored. Irrespective of whether stimuli had been actively classified by pressing a key or participants had merely attended to verbal codes denoting class and action, the resulting S-R associations transferred from one stimulus format to the other suggesting that stimuli were represented in abstract format. This finding again underlines the striking structural similarity of S-R associations formed based on task execution and verbal coding and further supports the notion that own action and attending to verbal codes presented together with a stimulus create equivalent S-R associations. Not only do S-R associations formed on the basis of verbal codes affect behavior independent from whether participants intend to apply them and are independent from working memory, suggesting their automatic nature (see Pfeuffer et al., 2017, for a detailed discussion), but the stimulus part of S-R associations formed on the basis of task execution as well as on the basis of verbal codes is represented in abstract format, allowing S-R associations to generalize across different perceptual representations of the same stimulus. Furthermore, the results of our experiments suggest that the formation of S-R association based on verbal coding is not restricted to pictorial exemplars, but both S-R associations based on task execution and verbal codes can also be established with word stimuli.

Yet, it has to be noted that it is not certain whether our findings regarding verbal code-based S-R associations can be generalized to situations in which participants do not attempt to memorize S-R mappings. A previous study (Pfeuffer et al., 2017) showed that whether participants merely attended to verbal codes or actively tried to memorize them did not affect the size of the priming effects observed for verbally

coded S-R mappings. But this study did not include switches in stimulus format between the prime and probe instances of stimuli. Therefore, as Experiment 1 did not include a group of participants that were not instructed to memorize the verbally coded S-R mappings, further studies are necessary to ascertain whether the present conclusions can be extended to situations in which participants do not explicitly attempt to memorize S-R mappings. Similarly, further studies should also explore whether the memorization of S-R mappings has an impact on execution-based S-R associations.

In prior studies investigating whether stimuli incorporated into S-R associations are represented in an abstract or specific format, task and response mapping were stable and predictable at test (Denkinger & Koutstaal, 2009; Horner & Henson, 2011; Schnyer et al., 2007). In contrast, in the study of Allenmark et al. (2015) and the present study, the classification task participants had to perform during probes as well as the classification-action mapping were pseudorandomly assigned so that neither probe classification task nor probe response mapping were predictable. Nevertheless, in line with the findings of Horner and Henson (2011) and Denkinger and Koutstaal (2009), Allenmark et al. as well as we found evidence for an abstract representation of stimuli within S-R associations. This suggests that neither the predictability of the classification task nor the predictability of the response mapping at test (i.e., during probing) affected how stimuli were incorporated into S-R associations. Regardless of the predictability of task and response mapping, stimuli were incorporated in an abstract format.

Importantly, however, so far all studies investigating the representational format of stimuli within S-R associations have employed designs in which stimulus format at test was predictable (Denkinger & Koutstaal, 2009; Horner & Henson, 2011; Schnyer et al., 2007; in Allenmark et al., 2015, stimulus format at test was predictable, but stimulus colour repeated/switched unpredictably). Consequently, participants might have

prepared to respond to the same stimuli depicted in the expected format. Future studies should therefore also include unpredictable switches of stimulus format during both primes and probes to investigate whether stimulus format predictability affects the format in which stimuli are incorporated into S-R associations.

Interestingly, we also replicate previous findings (Pfeuffer et al., 2017), suggesting that verbally coded S-R associations are less pronounced in terms of their behavioral impact in comparison to S-R associations based on task execution. Prior studies indicated that both facilitation (repetition priming; e.g., Logan, 1990) and interference (e.g., Horner & Henson, 2011, 2012) are reflected in item-specific priming effects (Horner & Henson, 2011, 2012; Moutsopoulou et al., 2015; Pfeuffer et al., 2017), suggesting the interaction of two processing routes, an automatic instance retrieval route relying on previously formed S-R associations and an algorithmic route computing responses anew (Horner & Henson, 2011). Responses automatically retrieved via the instance retrieval route can compete with responses generated via the algorithmic route giving rise to interference effects evident in reduced performance for switches in S-R mapping between prime and probe (Horner & Henson, 2011). As differences in the size of the behavioral effects associated with switches in S-R mappings between executed and verbally coded blocks have replicated across several experiments, these differences might stem from an absence (or marked reduction) of either facilitation or inhibitory processes in verbally coded blocks. Such an absence of either facilitation or interference would also be informative regarding the processes underlying verbal code-based priming effects, that is, the processes underlying automaticity in the absence of action (i.e., without prior practice). The present study was not designed to differentiate between facilitation and interference and therefore could not address this question. Future studies should therefore additionally include

novel stimuli during probe trials to dissociate facilitatory and interference processes for S-R priming effects based on active task execution and verbal coding.

Overall, our finding that both the stimulus part of executed and verbally coded S-C and S-A associations is represented in abstract format indicates a strong degree of generalizability for the resulting S-R associations. We observed that S-R associations formed for object names affected performance on images of specific corresponding objects (and vice versa), suggesting that S-R associations encompassed an abstract stimulus representation that allowed perceptually different representations of the same stimulus to automatically activate associated responses. Thus, our findings not only extend our knowledge about the representational format of the stimulus part of S-R associations based on task execution to S-R associations based on verbal codes, but also indicate that automatized behavior is more adaptive than previously thought. Not only can automaticity be achieved without prior own action, but automatisms acquired during own action as well as in the absence of own action can also generalize to different perceptual stimulus representations and exemplars.

### **Compliance with Ethical Standards**

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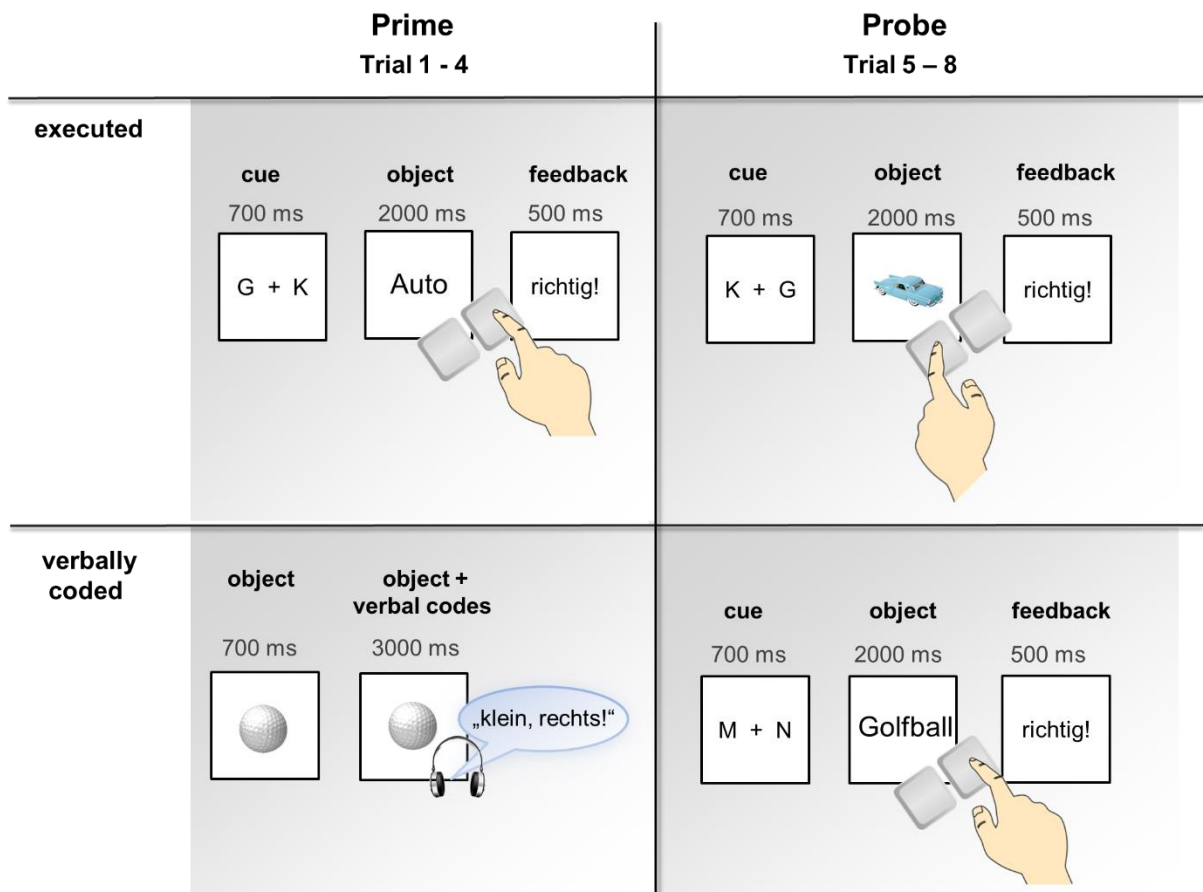
All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

### References

- Allenmark, F., Moutsopoulou, K., & Waszak, F. (2015). A new look on S-R associations: how S and R link. *Acta Psychologica, 160*, 161-169.
- Brady, T. F., Konkle, T., Alvarez, G. A., & Oliva, A. (2008). Visual long-term memory has a massive storage capacity for object details. *Proceedings of the National Academy of Sciences of the United States of America, 105*, 14325 - 14329.
- Denkinger, B., & Koutstaal, W. (2009). Perceive-decide-act, perceive-decide-act: How abstract is repetition-related decision learning?. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35*, 742-756.
- Dennis, I., & Schmidt, K. (2003). Associative processes in repetition priming. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29*, 532-538.
- Dobbins, I. G., Schnyer, D. M., Verfaellie, M., & Schacter, D. L. (2004). Cortical activity reductions during repetition priming can result from rapid response learning. *Nature, 428*, 316-319.
- Henson, R. N., Eckstein, D., Waszak, F., Frings, C., & Horner, A. J. (2014). Stimulus–response bindings in priming. *Trends in cognitive sciences, 18*, 376–384.
- Hommel, B. (1998). Event files: Evidence for automatic integration of stimulus–response episodes. *Visual Cognition, 5*, 183-216.
- Horner, A. J., & Henson, R. N. (2009). Bindings between stimuli and multiple response codes dominate long-lag repetition priming in speeded classification tasks. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 35*, 757–779.
- Horner, A. J., & Henson, R. N. (2011). Stimulus–response bindings code both abstract and specific representations of stimuli: Evidence from a classification priming design that reverses multiple levels of response representation. *Memory & Cognition, 39*, 1457-1471.



- Horner, A. J., & Henson, R. N. (2012). Incongruent abstract stimulus–response bindings result in response interference: fMRI and EEG evidence from visual object classification priming. *Journal of Cognitive Neuroscience*, *24*, 760-773.
- Hsu, Y. F., & Waszak, F. (2012). Stimulus-classification traces are dominant in response learning. *International Journal of Psychophysiology*, *86*, 262-268.
- Logan, G. D. (1988). Toward an instance theory of automatization. *Psychological Review*, *95*, 492-527.
- Logan, G. D. (1990). Repetition priming and automaticity: Common underlying mechanisms?. *Cognitive Psychology*, *22*, 1-35.
- Moutsopoulou, K., Yang, Q., Desantis, A., & Waszak, F. (2015). Stimulus-Classification and Stimulus-Action Associations: Effects of repetition learning and resilience. *Quarterly Journal of Experimental Psychology*, *68*, 1744-1757.
- Pfeuffer, C. U., Moutsopoulou, K., Pfister, R., Waszak, F., & Kiesel, A. (2017). The Power of Words: On item-specific stimulus-response associations formed in the absence of action. *Journal of Experimental Psychology: Human Perception and Performance*, *43*, 328-347.
- Schnyer, D. M., Dobbins, I. G., Nicholls, L., Davis, S., Verfaellie, M., & Schacter, D. L. (2007). Item to decision mapping in rapid response learning. *Memory & Cognition*, *35*, 1472-1482.
- Waszak, F. (2010). Across-task long-term priming: interaction of task readiness and automatic retrieval. *The Quarterly Journal of Experimental Psychology*, *63*, 1414-1429.
- Waszak, F., Hommel, B., & Allport, A. (2003). Task-switching and long-term priming: Role of episodic stimulus–task bindings in task-shift costs. *Cognitive Psychology*, *46*, 361-413.



*Figure 1.* Structure of executed and verbally coded blocks in Experiment 1. Four prime trials were followed by four probe trials (prime-probe lag 2-7 trials). Each object appeared only once as a prime and once as a probe. Objects either appeared as object names (word format) during their prime trial and as object images (image format) during their probe trial or vice versa. Participants actively classified objects in probe trials and executed prime trials by pressing the key spatially corresponding to the correct object classification. In verbally coded prime trials, verbal codes denoting class and action were presented while participants passively viewed the objects. The structure of Experiment 2 was equivalent with the exception that stimuli were consistently presented as object names.

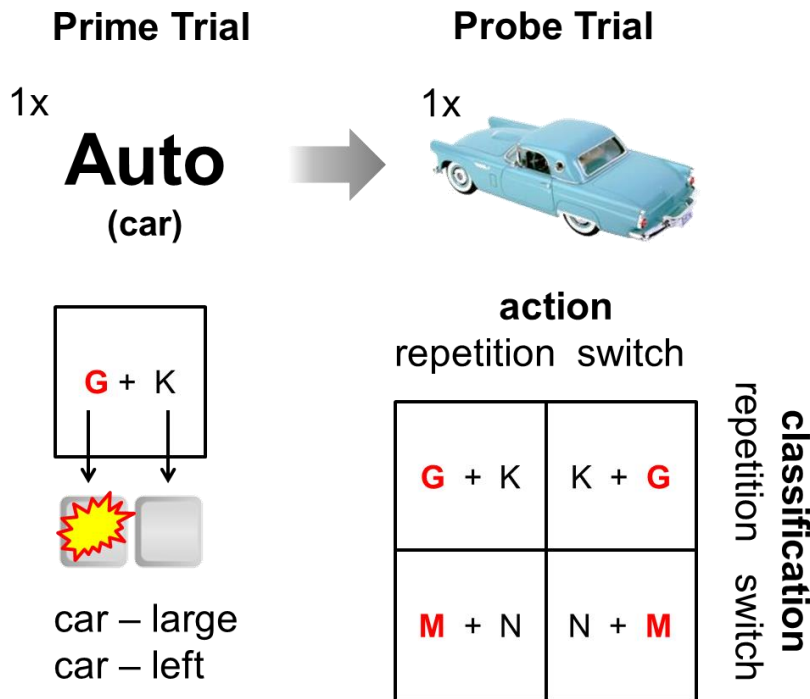


Figure 2. Schematic overview of the item-specific repetitions/switches in S-A and S-C mapping (i.e., action and classification mapping) between the prime and probe instance of a stimulus as indicated by the task cues (size task: “K + G” and “G + K” – K = “klein”/small, G = “groß”/large; mechanism task: “M + N” and “N + M” – M = “mechanisch”/mechanic, N = “nicht-mechanisch”/non-mechanic). In executed prime trials (depicted), participants classified stimuli by pressing a left or right key corresponding to the correct classification as indicated by a task cue. In verbally coded prime trials, participants attended to the stimuli and were presented with verbal codes denoting class and action (e.g., “large, left”). For probe trials, S-A and S-C mappings were then varied orthogonally and each combination of classification and action mapping occurred equally frequently for the two prime types (executed and verbally coded) and the two prime-probe formats (image-word vs. word-image; Experiment 1 only). Correct classifications are marked as red and bold. Correct actions are indicated by the spatial position of the letter corresponding to the correct classification.

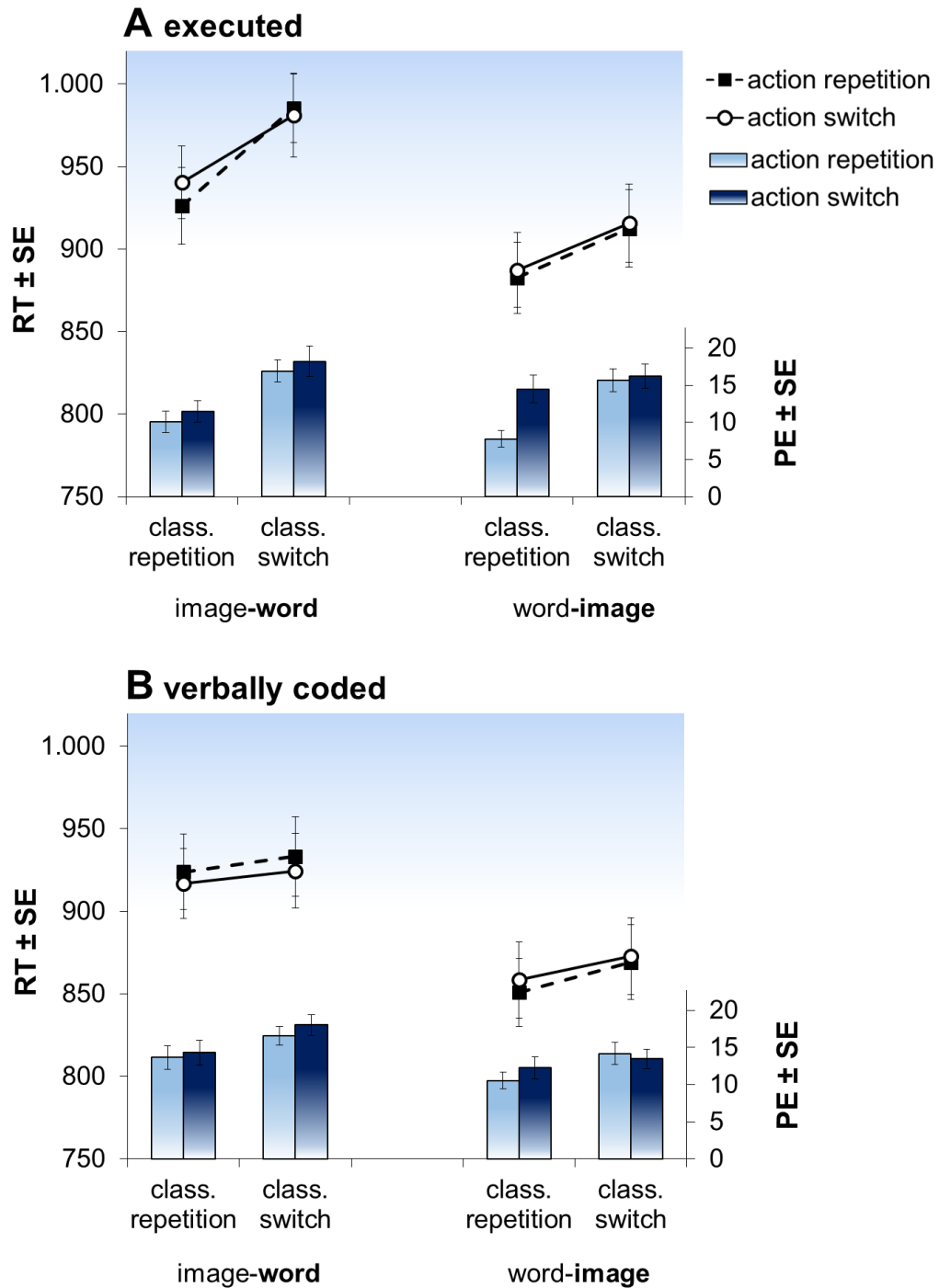


Figure 3. RT and PE results of Experiment 1. Probe trial reaction times (RTs in ms; lines) and percentages of errors (PEs in %; bars) are displayed for A) executed blocks and B) verbally coded blocks. Probe trial results are displayed separately for the two prime-probe formats (image-word vs. word-image) and the four possible switch conditions (classification: repetition vs. switch; action: repetition vs. switch).

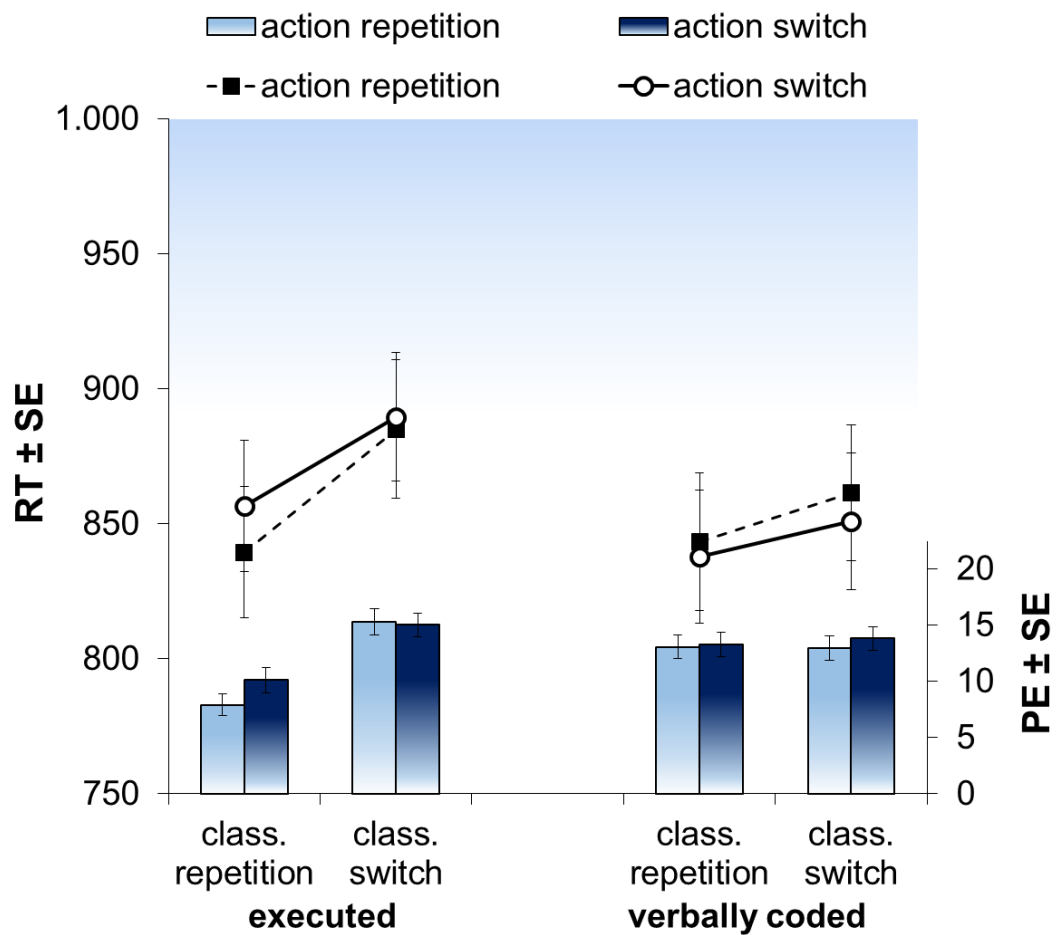


Figure 4. Probe trials RT and PE results of Experiment 2. Reaction times (RTs in ms; lines) and percentages of errors (PEs in %; bars) are displayed separately for the two prime types (executed vs. verbally coded) and the four possible switch conditions (classification: repetition vs. switch; action: repetition vs. switch).

Table 1. Mean reaction time (RT) and error rate (percentage of errors, PE) switch costs in the probe trials by prime-probe format (image-word vs. word-image), prime type (executed vs. verbally coded), switch type (classification vs. action), and experiment.

			image - word		word - image	
			format switching	format constant	format switching	format constant
			Exp. 1	Exp. 2	Exp. 1	Pfeuffer et al. (2017)
<i>RT</i>	<b>executed</b>	action	2.57	12.55	5.27	13.61
		classification	30.60	39.90	49.84	55.40
	<b>verbally coded</b>	action	5.97	-8.33	-8.59	10.39
		classification	16.16	15.92	9.13	13.71
<i>PE</i>	<b>executed</b>	action	3.58	1.07	1.22	2.20
		classification	4.69	6.15	6.75	5.58
	<b>verbally coded</b>	action	0.59	0.61	1.09	-0.05
		classification	2.28	0.19	3.30	2.62

## Appendix

### Experiment 1

**Prime RT and PE analyses.** We used a 2 x 2 x 2 repeated measures ANOVA with the within-subjects factors prime-probe format, classification, and action to investigate possible a priori differences between conditions in executed blocks. Trials in verbally coded blocks were not analyzed as they did not contain any performance measures. Both the analysis of prime RTs and the analysis of prime PEs revealed a significant difference in performance between object images and object names, RTs:  $F(1,38) = 64.05, p < .001, \eta_p^2 = .63$ , PEs:  $F(1,38) = 8.25, p = .007, \eta_p^2 = .18$ . Object images were classified faster and more accurately than object names. All other RT,  $F_s \leq 1.60, p_s \geq .214, \eta_p^2 \leq .04$ , and PE effects,  $F_s \leq 1.73, p_s \geq .197, \eta_p^2 \leq .04$ , failed to reach significance.

**Memory recall analyses.** Participants recalled 49.8% of prime actions (50.2% executed, 49.5% verbally coded) and 62.1% of prime classifications (62.3% executed, 61.8% verbally coded). One sample t-test showed that participants recall performance for actions did not significantly differ from chance (50%) for any combination of prime type and prime-probe format,  $t(38) \geq -1.09, p_s \geq .282, d_s \leq 0.17$ . Performance on classification recall trials was significantly above chance (50%) for all combinations of prime type and prime-probe format,  $t(38) \geq 3.54, p_s \leq .001, d_s \geq 0.57$ .

A 2 x 2 x 2 repeated measures ANOVA with the within-participants factors memory type (action vs. classification), prime type (executed vs. verbally coded), and prime stimulus type (image vs. word) showed that recall performance was significantly better for classifications than for actions,  $F(1,38) = 44.60, p < .001, \eta_p^2 = .54$ . Furthermore, participants were significantly better at recalling the classifications for stimuli primed as pictures in comparison to stimuli primed as words,  $F(1,38) = 8.45, p = .006, \eta_p^2 = .18$ . Finally, memory type and prime stimulus type significantly interacted,

$F(1,38) = 16.83, p < .001, \eta_p^2 = .31$ . Both for stimuli primed as pictures,  $t(38) = 8.00, p < .001, d = 1.28$ , and for stimuli primed as words,  $t(38) = 3.89, p < .001, d = 0.62$ , participants were significantly better at recalling classifications in comparison to actions. The effect of memory type was, however, more pronounced for stimuli primed as pictures. All other effects failed to reach significance,  $F_s \leq 2.98, p_s \geq .092, \eta_p^2 \leq .07$ .

**Discussion.** The prime analyses revealed that RTs and PEs were higher when participants classified object names rather than object images. Apart from performance differences between prime-probe formats, no a priori differences between conditions were observed. Replicating the findings of Pfeuffer et al. (2017), we found that memory recall performance was better for classifications than for actions. Participants' recall performance for classifications was above chance level, whereas their action recall performance did not differ from chance. Interestingly, recall performance was overall better for stimuli primed as pictures in comparison to stimuli primed as words and the recall performance differences between action and classification were more pronounced for stimuli primed as pictures.

## Experiment 2

**Prime RT and PE analyses.** To explore possible a priori differences between conditions, 2 x 2 repeated measures ANOVAs with the factors classification and action were conducted on prime RTs and PEs. Neither the RT analysis,  $F_s \leq 1.74, p_s \geq .195, \eta_p^2 \leq .04$ , nor the PE analysis,  $F_s < 1$ , revealed any significant differences.

**Memory recall analyses.** Participant recalled 56.0% of actions in executed blocks and 66.0% of actions in verbally coded blocks. In executed blocks, they recalled 64.3% of classifications and in verbally coded blocks they recalled 66.8%. One sampled t-test showed that participants' recall performance was significantly above chance level (50%) for both action and classification recall and both prime types,  $t(39) \geq 3.12, p_s \leq .001, d_s \geq 0.67$ .



A 2 x 2 repeated measures ANOVA with the factors memory type (classification vs. action) and prime type (executed vs. verbally coded) showed that participants recalled classifications more accurately than actions,  $F(1,39) = 12.28, p = .001, \eta_p^2 = .24$ . Furthermore, recall performance was significantly better in verbally coded blocks as compared to executed blocks,  $F(1,39) = 10.37, p = .003, \eta_p^2 = .21$ . Memory type (classification vs. action) and prime type significantly interacted,  $F(1,39) = 8.88, p = .005, \eta_p^2 = .19$ . Recall performance was significantly better for classifications in comparison to actions in executed blocks,  $t(39) = 4.53, p < .001, d = 0.72$ , but not in verbally coded blocks,  $t(39) = 0.42, p = .680, d = 0.07$ .

**Discussion.** We did not observe any a priori differences between conditions during prime trials that could have accounted for our probe trial results. Moreover, in line with previous findings (Pfeuffer et al., 2017) recall performance was above chance for both action and classification recall, with classification recall performance being better than action recall performance. However, contrary to the findings of Pfeuffer et al. (2017), classification recall performance only exceeded action recall performance in executed blocks, but not in verbally coded blocks.