The Power of Words: On Item-Specific Stimulus–Response Associations Formed in the Absence of Action

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Research on stimulus–response (S-R) associations as the basis of behavioral automaticity has a long history. Traditionally, it was assumed that S-R associations are formed as a consequence of the (repeated) co-occurrence of stimulus and response, that is, when participants act upon stimuli. Here, we demonstrate that S-R associations can also be established in the absence of action. In an item-specific priming paradigm, participants either classified everyday objects by performing a left or right key press (task-set execution) or they were verbally presented with information regarding an object's class and associated action while they passively viewed the object (verbal coding). Both S-R associations created by task-set execution and by verbal coding led to the later retrieval of both the stimulus–action component and the stimulus–classification component of S-R associations. Furthermore, our data indicate that both associations created by execution and by verbal coding are temporally stable and rather resilient against overwriting. The automaticity of S-R associations formed in the absence of action reveals the striking adaptability of human action control.

Public Significance Statement

Research on associative learning has shown that when we act upon stimuli—for instance, when we stop our car in front of a red traffic light—associations are formed between the respective stimuli (i.e., the red traffic light) and our actions (i.e., hitting the brake pedal). Due to these associations, previous actions are retrieved automatically when a stimulus recurs. That is, we do not need to elaborate on the action again and sometimes even reperform the same action contrary to our current intentions. Here, we provide evidence that acting upon stimuli is not necessary to associate stimuli and responses. Instead verbal information denoting action and stimulus classification presented simultaneously with a stimulus is apparently bound to it and supports the respective action when the stimulus is reencountered. These findings suggest that behavioral automaticity can be achieved without prior practice.

Keywords: stimulus–response associations, associative learning, verbal codes, automaticity

Behavioral automaticity allows us to exert the majority of our everyday actions smoothly and without a need for further controlled processing. This behavioral automaticity is largely enabled by stimulus–response (S-R) associations, formed by the repeated co-occurrence of stimuli and responses, which render stimuli able to automatically trigger their associated responses (e.g., Henson, Eckstein, Waszak, Frings, & Horner, 2014; Hommel, 1998; Logan, 1990). The notion that stimuli and responses bind together due to

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repeated co-occurrence is supported by effects of (item-specific) repetition priming (e.g., Dennis & Schmidt, 2003; Dobbins, Schnyer, Verfaellie, & Schacter, 2004; Logan, 1988, 1990). For instance, in speeded object classification tasks, participants respond faster to items with the same response they previously executed for the item rather than with a different response.

Further support for the idea of S-R associations comes from neuroimaging studies showing that when a stimulus reoccurs, response repetitions lead to decreased neuronal activity (repetition suppression) in frontal regions, reflecting facilitated processing, whereas response switches are associated with increased frontal activity, indicating interference (Horner & Henson, 2008; Race, Shanker, & Wagner, 2009; Horner & Henson, 2012). These findings demonstrate that participants had formed S-R associations which they automatically retrieved when responses repeated and had to counteract when responses switched. S-R associations, thus, seem to allow for rapid and automatic control over the agent's behavioral repertoire.

Recently, several studies (e.g., Horner & Henson, 2009; Hsu & Waszak, 2012; Moutsopoulou, Yang, Desantis, & Waszak, 2015; Waszak, 2010; Waszak, Hommel, & Allport, 2003) have shown that a single prime trial is sufficient to create an S-R association. For instance, Horner and Henson (2009) used a speeded prime–probe classification task, in which participants classified object images according to their size. They showed that after having classified a stimulus once in a prime trial, reaction times (RTs) in response to the same object image increased when the action or classification switched rather than repeated in a later probe trial (Horner & Henson, 2009).

However, although it has also been shown that mere task-set instructions can affect behavior (e.g., Brass, Wenke, Spengler, & Waszak, 2009; Cohen-Kdoshay & Meiran, 2007, 2009; Kiesel, Wendt, & Peters, 2007; Liefooghe, Wenke, & De Houwer, 2012; Waszak, Pfister, & Kiesel, 2013; Waszak, Wenke, & Brass, 2008; Wenke, De Houwer, De Winne, & Liefooghe, 2015; Wenke & Frensch, 2005; Wenke, Gaschler, & Nattkemper, 2007), such findings can be explained by the notion of a prepared reflex that is preset during preparation and then initiated once a stimulus condition is met (e.g., Hommel, 2000; Kiesel, Kunde, & Hoffmann, 2007; Kunde, Kiesel, & Hoffmann, 2003; Woodworth, 1938). So far, no study supported the notion that automatic S–R associations can be formed in the absence of action. We use the term automatic S-R associations to describe associations that lead to automatic S-R translation without action intention. That is, even when participants do not intend to respond according to the S-R mappings. Thus, task-set instructions, that affect behavior only while participants intend to apply them, are not considered to be automatic S-R associations according to our narrow definition of automaticity.

An example of task-set instruction effects was reported by Cohen-Kdoshay and Meiran (2007, 2009) and Meiran and Cohen-Kdoshay (2012) who showed that merely instructed flanker responses affected performance in the first trials of an Eriksen flanker task. Similarly, Liefooghe et al. (2012) demonstrated that RTs are shorter when the response required by the current task matches rather than mismatches the response required by a merely instructed subsequent task. Yet, instruction-based effects do emerge only when three preconditions are met (Meiran, Cole, & Braver, 2012): First, the retrieval of merely instructed task-sets relies on the availability of storage resources in the region of direct access (see Oberauer, 2002, 2010), an equivalent of working memory responsible for forming bindings. Second, instructed S-R links only affect behavior when held in a plan-to-execution event. This means from the point of planning until the point of plan execution, that is, until the intended goal has been realized. And third, participants must be motivated to form and apply a plan. This has been demonstrated in experiments where motivation was compromised, because the execution of the instructed mapping was frequently omitted (Wenke, Gaschler, Nattkemper, & Frensch, 2009). Thus, instructions only affect behavior as long as the intention to apply them is still active.

Given that both working memory capacity and an intention to apply instructions are necessary for instructions to affect behavior and that instructions can only be effective within a plan-to-execution event (Meiran et al., 2012), it is clearly evident that mere instruction does not allow for automatic S-R translation. Here, in three experiments, we aimed at comprehensively investigating whether automatic S-R associations can be formed in the absence of action. To this end, we drew on an item-specific priming paradigm (Hsu & Waszak, 2012; Moutsopoulou et al., 2015) that has recently been put forward to distinguish between two components of S-R associations: stimulus–action (S-A) and stimulus–classification (S-C) associations (for a similar distinction, see Horner & Henson, 2008, 2009; Moutsopoulou & Waszak, 2012, 2013; Race, Badre, & Wagner, 2010). S-A associations are regarded as associations between a stimulus and the action, that is, the motor output, performed in response to it, whereas S-C associations are associations between a stimulus and the task-specific stimulus category it is linked to (usually its classification as belonging to a certain semantic category).

In this item-specific priming paradigm, the participants' task was to classify everyday objects either according to their size or according to whether they were mechanical or not by pressing a left or right key. Task cues preceding the object images were used to independently indicate the classification and action for a specific stimulus. For example, the task cue " G + K" indicated that an object image had to be classified according to its size (G for German "groβ" = large, K for German "klein" = small) by pressing a left key for the classification "large" and a right key for the classification "small." Conversely, the task cue "K + G" indicated that a left key press corresponded to the classification "small" and a right key press to the classification "large" (see Figure 1). Alternatively, the task cues "M + N" or "N + M" indicated that object images should be classified as being mechanical (M) or nonmechanical (N). Each object appeared as a prime and as a probe with a lag of several trials between its prime and probe instance. Orthogonally repeating or switching S-A and S-C mappings between the prime and probe instance of an object allowed for the independent assessment of S-A and S-C associations (see Figure 2). Robust interference effects, that is, RT and error rate increases for mapping switches rather than repetitions, were found for both S-A and S-C mappings (Moutsopoulou et al., 2015).

Using the same design, we contrasted prime trials with action and without action. Prime trials with action (executed) were equivalent to those of Moutsopoulou et al. (2015) and participants actively classified objects by pressing a key. In prime trials without action (verbally coded), participants did not receive a task cue and did not perform an action to classify the object image. Instead, they
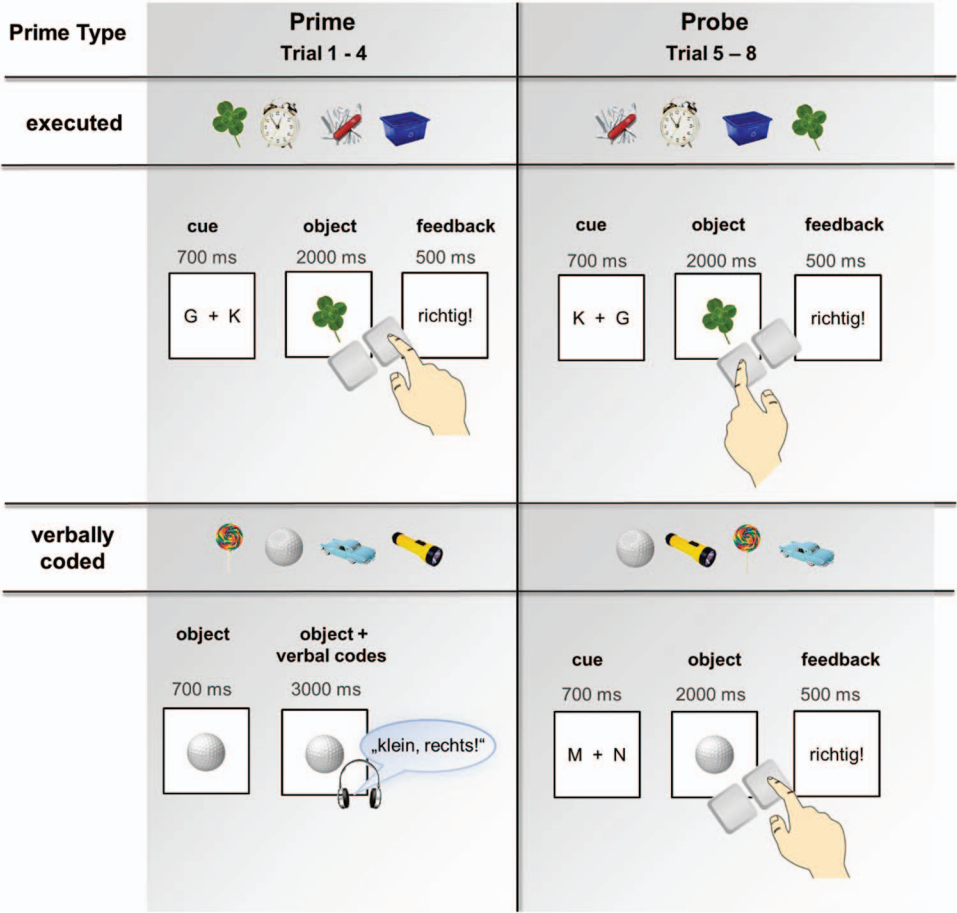
Figure 1.   Structure of executed and verbally coded blocks in Experiment 1. Four prime trials were followed by four probe trials (prime–probe lag two to seven trials). For executed blocks, prime and probe trials were equivalent and consisted of the presentation of a cue (700 ms) followed by the picture of an object that participants had to categorize by pressing the key corresponding to the cued mapping. Object pictures were presented until participants responded or until 2,000 ms had passed and followed by 500 ms of feedback (German "*richtig*!/*falsch*!" for "correct!/incorrect!"). In the verbally coded blocks, prime trials consisted of 700 ms of object image presentation followed by another 3,000 ms of object presentation accompanied by voice instruction containing the object's class as well as its associated action (e.g., German "*klein*, *rechts*!" meaning "small, right!"). Participants passively viewed the object images and did not perform any response during prime trials in verbally coded blocks. Probe trials in verbally coded blocks were equivalent to probe trials in executed blocks. See the online article for the color version of this figure.

passively viewed the object and were verbally presented with two words denoting the object's class and a to-be-associated action (verbal codes). For example, they heard the German words "*klein*, *links*" (meaning "small, left") to denote that an object belongs to the class "small" and is mapped to the action "left" (see Figure 1, lower panel).

For both prime instances with action (executed) and without action (verbally coded), probe trials were identical and always required the active classification of an object via a left/right key press. As in the original study by Moutsopoulou et al. (2015), S-A and/or S-C mappings repeated or switched between the prime and probe instance of the same object. Crucially, participants did not have to actually execute the S-A and S-C mappings presented to them in verbally coded blocks at any point during the experiment. If automatic S-A and S-C associations were formed during prime

trials and automatically retrieved during probe trials, reactions should be faster and more accurate during probes for S-A/S-C repetitions rather than S-A/S-C switches. We hypothesized that this should be the case both when participants had acted upon stimuli during prime trials and when participants had only passively attended to coinciding verbal codes while viewing stimuli, suggesting that automatic S-R associations can be formed even in the absence of action.

In addition to the S-A/S-C manipulation of Moutsopoulou et al. (2015), the crucial variation in the current study was whether during prime instances participants actively executed S-R mappings by pressing a left/right key, thus classifying the object, or whether participants merely passively attended to the verbal codes for the object's class and action while viewing the object. Additionally, in Experiment 1, we manipulated whether participants
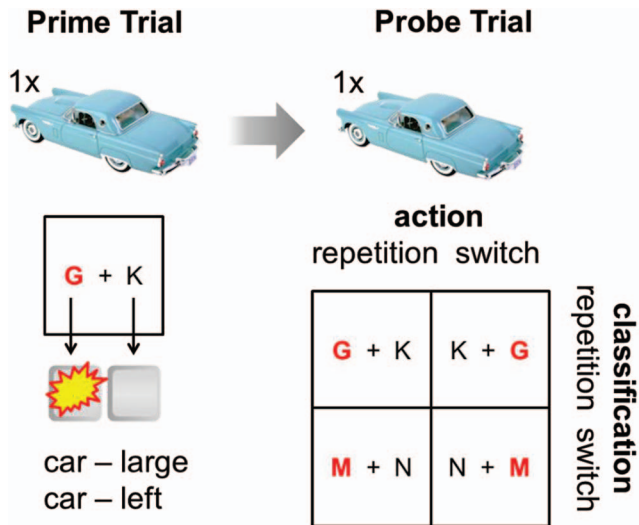
Figure 2. Schematic overview of the critical experimental variation to test for stimulus–action (S-A) and stimulus–classification (S-C) associations independently. The four different switch conditions possible for the *probe* trial resulted from the orthogonal combination of the factors classification (repetition vs. switch) and action (repetition vs. switch). Correct classifications are marked as red and bold, and correct actions are indicated by the spatial position of the letter corresponding to correct classification. The task cues "G + K" (G—German "groß", large; K—German "klein", small), "K + G", "M + N" (M—mechanical; N—nonmechanical), and "N + M" indicate the currently required classification (large—small or mechanical—nonmechanical) and action (e.g., G on the left/right side means that a large item requires a corresponding left/right response). See the online article for the color version of this figure.

had to memorize primed S-A and S-C mappings or were merely instructed to attend to them. Still, participants were not instructed to apply S-A and S-C mappings, encountered during prime trials, during probe trials. Instead, with this memory instruction, we varied whether verbal codes were relevant at least for some aspects of task performance (recall group) or did not bear any relevance for task performance (no recall group).

To foreshadow the results, we demonstrate that both S-A and S-C associations are formed when verbal codes are presented simultaneously with stimuli during prime trials. We further demonstrate that this is the case irrespective of the relevance of these verbal codes for task performance.

Experiments 2 and 3 investigated the temporal stability and resilience against overwriting of associations based on verbal codes in comparison to execution-based associations. These experiments demonstrate that both types of associations, execution-based S-R associations and S-R associations based on verbal codes, are rather resilient and temporally stable.

Experiment 1

In Experiment 1, we investigated whether automatic S-A and S-C associations could be instantiated both in the presence (executed blocks) and absence of action (verbally coded blocks). We did so by contrasting the effects of prime trials in which participants actively classified stimuli via key presses and prime trials in which verbal codes regarding class and action were presented simultaneously with stimuli while participants passively attended. Furthermore, Experiment 1 explored whether the relevance of the presented verbal codes to task performance modulated the formation and/or retrieval of S-R associations based on verbal codes. This was investigated by comparing two between-subjects groups that either had to or did not have to memorize and recall the presented verbal codes.

Method

Participants. Forty participants were recruited (10 male, three left-handed; M_{age} = 23.0 years) and provided written informed consent. Sample size was determined according to the effect size reported in previous studies using the item-specific priming paradigm (Moutsopoulou et al., 2015).

Each participant was randomly assigned to one of two memory recall groups—(a) no memory recall (no recall group) or (b) memory recall for both verbally coded and executed blocks (recall group)—resulting in 20 participants per memory recall group.

One participant of the no recall group was excluded from all analyses, because of errors or response omissions in more than 30% of the trials. Two additional participants were excluded, because they reported having taken off their headphones. These three participants were replaced by new participants.

Stimuli and apparatus. Participants sat approximately 60 cm from a 17-in. CRT screen (1,024 pixels × 768 pixels) in a dimly lit, sound-attenuated room. They wore headphones and their index fingers rested on two external keys placed in front of them to the left and right (key distance 13.5 cm).

Participants classified object images either according to size or mechanism. For size classification, participants judged whether or not the corresponding real-life size objects fitted into a reference box (box dimensions: 37.5 cm × 30 cm × 13.5 cm) and for mechanism classification participants judged whether or not objects contained a mechanism (e.g., wheels, a switch, or electronic parts). 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 "nonmechanical" ("*nicht-mechanisch*"). Objects had to be classified by pressing the response key (left vs. right) that spatially corresponded to the correct object classification.

We used 512 object images (256 pixels × 256 pixels, about 8° visual angle) from a set by Brady, Konkle, Alvarez, and Oliva (2008) and Moutsopoulou et al. (2015). The target set comprised of 128 images in each category (small mechanical, small nonmechanical, large mechanical, large nonmechanical). All images depicted distinct, familiar and easy to categorize objects regarding size and mechanism classification. Each item was presented only twice throughout the experiment, once as a prime and once as a probe. Twenty-four additional object images were used in a preceding practice of the task.

Verbal codes regarding class and action were presented via voice recording playbacks (1.8–2.3 s) featuring a neutral, female voice. Recordings first informed participants about the class and then about the action associated with an object (e.g., "*klein, rechts*," English "small, right").

Design and procedure.   The experiment used an item-specific priming paradigm with each item being presented once as a prime and once as a probe. In different blocks of the experiment, participants either actively classified prime targets by executing a response (executed blocks) or they were provided with a verbal code that informed them about one class and action mapping while they passively viewed stimuli during primes (verbally coded blocks). The experiment consisted of eight practice blocks of eight trials each (four executed, four verbally coded) and 128 blocks of eight trials each in the main experiment (64 executed, 64 verbally coded; 1,024 trials total).

Blocks were subdivided into a prime miniblock of four trials followed by a probe miniblock of four trials. Four object images were randomly chosen as primes of a block. The same four objects were subsequently probed within the same block (prime–probe lag of two to seven trials, see Figure 1). Each block randomly featured either executed or verbally coded prime trials throughout. Executed prime trials required participants to indicate the correct classification of an object by performing the action corresponding to the correct object classification as displayed in the cue. In verbally coded prime trials participants passively viewed the object image and listened to a voice recording informing them about the class and action associated with the object (e.g., "*klein, rechts*," English "small, right"). Participants were informed about the prime type of the next block in advance and probe trials were identical for both block types (for details regarding the trial procedure during prime and probe, see Figure 1).

S-A and S-C mappings, respectively, either repeated or switched between primes and probes resulting in four switch conditions (full repetition, action switch, classification switch, full switch; see Figure 2). Analyses were conducted on the probe trials only. The data were analyzed item specifically, that is, performance measures were analyzed depending on repetitions versus switches in S-A and/or S-C association between primes and corresponding probes.

In the recall group, participants were instructed to try and memorize the prime S-A and S-C mapping (for both executed and verbally coded blocks). That is, they either had to memorize how they themselves classified objects when they first appeared as primes and which action they performed to indicate this classification (executed blocks) or they had to memorize the verbal codes for class and action presented to them via the headphones (verbally coded blocks). Whereas the block ended with the last probe trial for the no recall group, for the recall group, an additional memory recall trial followed the probe trials. For this memory recall trial, one of the four items primed within the same block was randomly selected to test participants' memory of the S-C and S-A mappings of the prime trial. The screen turned gray and participants were again presented with one of the four objects of that block, displayed centrally on screen. First classification memory recall was performed and then action memory recall. For classification memory recall, the text "*Kategorie*?" ("category?") above the image prompted participants to press the key on the keyboard corresponding to the class of the displayed object during the prime trial ("K" for "*klein*"/"small," "G" for "*groß*"/"large," "M" for "*mechanisch*"/"mechanic," and "N" for "*nicht-mechanisch*"/"nonmechanic"). Subsequently, the prompt "*Reaktion* R/L?" ("reaction R/L?") indicated that participants should perform the action (left vs. right key press) that the object had been associated with during

the prime trial. Participants were informed that speed was not essential during memory recall and were asked to try and remember the class and action they heard/performed as well as possible.

Participants were told to always put their fingers on the response keys at the beginning of a block to avoid delays in verbally coded probe trials. They were specifically instructed not to perform any responses during verbally coded primes, but to only passively attend to the verbal codes regarding class and action. During practice trials, participants were reminded of these instructions if they failed to position their hands in time or accidentally responded. Furthermore, during verbally coded primes, responses were recorded and trials with accidental responses were discarded from analyses.

Results

The first probe trial of each block was excluded to account for possible influences of the switch from passive listening to active responding in verbally coded blocks. Furthermore, trials with response omissions (0.3%) were excluded from all analyses and trials with commission errors (10.2%) were excluded from RT analyses. For the crucial analyses of probe trial RTs and percentages of error (PEs) only probe trials with correct responses in the corresponding prime trial were used (6.2% of trials were excluded due to erroneous prime trials). In addition, verbally coded prime trials on which participants accidentally responded (0.3%) as well as their corresponding probe trials were excluded from all analyses. On average, for RT analyses, 15.7% of probe trials were discarded due to these restrictions. Outliers, that is, RTs deviating from their corresponding cell mean by 3 *SD* or more, calculated separately for participants and conditions, were removed from RT analyses (1.1% of the trials). In the following, we focus on analyses of RTs and PEs in the probe trials (see Figure 3 and Table 1).

Participants in the recall group responded correctly on 67.2% of class recall trials (executed: 64.1%, verbally coded: 70.4%) and 63.7% of action recall trials (executed: 59.1%, verbally coded: 68.3%). One sample *t* tests comparing recall performance to chance level (50%) showed that participants performance was significantly above chance for both class and action recall both in executed and verbally coded blocks, $ts \geq 4.69$, $ps \leq .001$, $ds \geq 1.05$. Additional prime trial analyses as well as an analysis of task switch costs in relation to Trial $n - 1$ can be found in the Appendix.

Probe RT analyses.   Probe trial RTs were submitted to a $2 \times 2 \times 2 \times 2$ mixed-design analyses of variance (ANOVA) with the between-subjects factor memory recall group (no recall vs. recall) and the within-subject factors prime type (executed vs. verbally coded), classification (repetition vs. switch), and action (repetition vs. switch). Classification and action switches were defined as item-specific switches between prime and corresponding probe.

Probe RTs were faster if the classification repeated rather than switched, $F(1, 38) = 47.41$, $p < .001$, $\eta_p^2 = .56$, and likewise if the action repeated rather than switched, $F(1, 38) = 8.18$, $p = .007$, $\eta_p^2 = .18$ (see Figure 3 and Table 1). The main effect of memory recall group was significant, $F(1, 38) = 9.77$, $p = .003$, $\eta_p^2 = .21$, with longer RTs in the recall group as compared to the no recall group. Furthermore, a significant main effect of prime type, $F(1, 38) = 23.58$, $p < .001$, $\eta_p^2 = .38$, was driven by faster responses
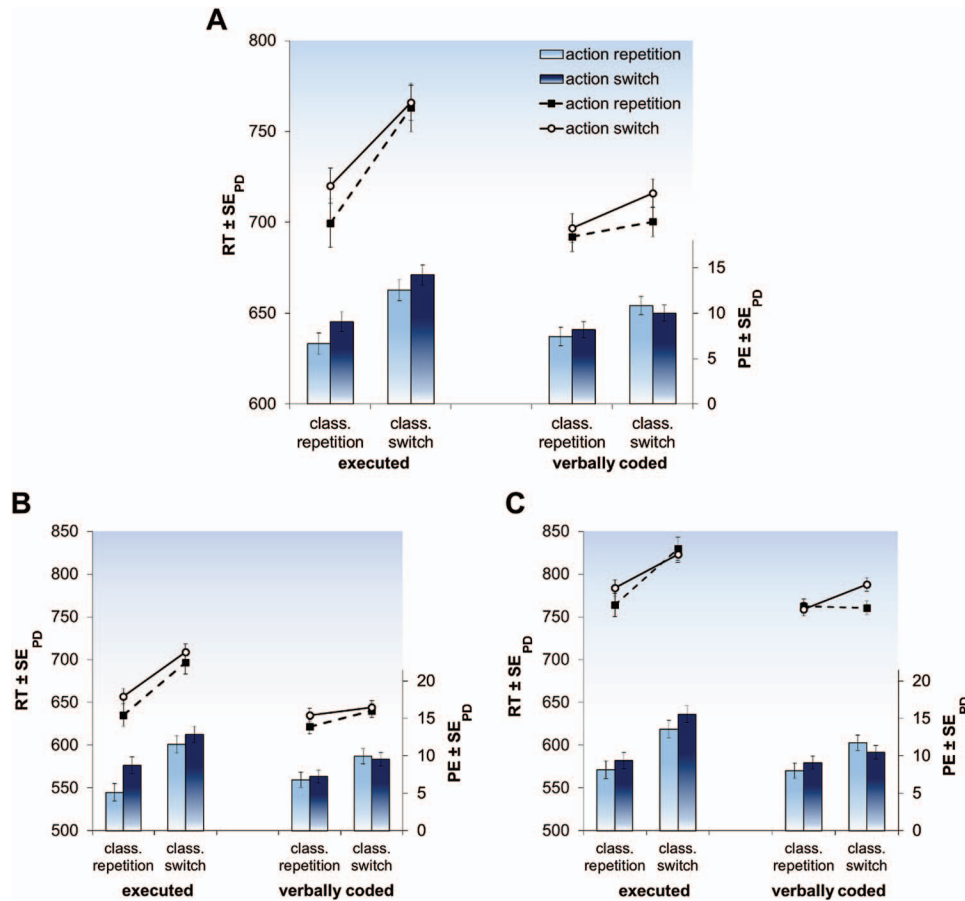
Figure 3. Main results of Experiment 1: Mean reaction times (RTs, in ms; lines) and percentages of errors (PEs, in %; bars) in the probe trials are displayed separately for the two prime types (executed vs. verbally coded) and four possible switch conditions (classification: repetition vs. switch; action: repetition vs. switch). Results are displayed for (A) both memory recall groups combined, (B) the no recall group, and (C) the recall group. Error bars indicate standard errors of paired differences (Pfister & Janczyk, 2013) that were computed separately for each classification switch condition. See the online article for the color version of this figure.

in verbally coded blocks compared to executed blocks.[1] Moreover, the interaction of prime type and classification was significant, $F(1, 38) = 24.25$, $p < .001$, $\eta_p^2 = .39$. RT increases associated with classification switches compared to classification repetitions were significantly more pronounced in executed blocks, $t(39) = 7.99$, $p < .001$, $d = 1.26$, as compared to verbally coded blocks, $t(39) = 2.40$, $p = .022$, $d = 0.39$. Yet, both RT differences were significant. All other effects failed to reach significance, $Fs \leq 2.86$, $ps \geq .099$, $\eta_p^2 \leq .07$. Even though the interaction of prime type and action did not reach significance, we conducted post hoc paired t tests to investigate the S-A effect separately for the two prime types, because the presence of S-A effects in verbally coded blocks is critical for the interpretation of our results. Significant RT increases associated with action switches relative to action repetitions were present in both executed blocks, $t(39) = 2.08$, $p = .044$, $d = 0.33$, and verbally coded blocks, $t(39) = 2.20$, $p = .034$, $d = 0.35$. For a simplified overview over the results, Figure 4A depicts the RT switch costs associated with classification switches ($\Delta RT_{\text{classification}} = RT_{\text{classification switch}} - RT_{\text{classification repetition}}$) vis-à-vis the effect of action switches ($\Delta RT_{\text{action}} = RT_{\text{action switch}} - RT_{\text{action repetition}}$).

Probe error trial analyses. Equivalent to the RT analysis, PEs were submitted to a $2 \times 2 \times 2 \times 2$ mixed-design ANOVA with the factors memory recall group, prime type, classification, and action. PEs were significantly higher for classification switches compared to repetitions, $F(1, 38) = 40.38$, $p < .001$, $\eta_p^2 = .52$ (see Figure 3 and 4B). Similarly, action switches showed a nonsignificant trend to produce higher PEs than action repetitions, $F(1, 38) = 3.61$, $p = .065$, $\eta_p^2 = .08$. The main effect of prime type was significant, $F(1, 38) = 7.68$, $p = .009$, $\eta_p^2 = .17$, with more errors being committed in executed blocks than in verbally coded blocks. Moreover, prime type significantly interacted with classification, $F(1, 38) = 8.07$, $p = .007$, $\eta_p^2 = .18$, with smaller switch-related PE increases in verbally coded than executed blocks, executed: $t(39) = 5.71$, $p < .001$, $d = 0.90$; verbally coded: $t(39) = 4.33$, $p < .001$, $d = 0.68$. Yet, both PE differences were significant. Finally, the interaction of prime type and action

[1] However, on probe trials with action and classification repetitions, RTs did not significantly differ between executed and verbally coded probes, $t(39) = 0.94$, $p = .353$, $d = 0.15$.

Table 1

Probe Trial Reaction Times (RTs, in ms) and Percentages of Errors (PEs, in %) in Experiment 1, Displayed Separately for the Two Memory Recall Groups (No Recall vs. Recall)

Memory recall group	Prime type	RTs				PEs			
		Classification repetition		Classification switch		Classification repetition		Classification switch	
		Action repetition	Action switch	Action repetition	Action switch	Action repetition	Action switch	Action repetition	Action switch
No recall	Executed	635	657	696	709	5.1	8.8	11.5	12.9
	Verbally coded	622	635	640	644	6.8	7.2	9.9	9.5
Recall	Executed	764	784	830	823	8.1	9.4	13.6	15.6
	Verbally coded	763	759	761	788	8.0	9.1	11.8	10.5
Overall									
Executed		700	720	763	765	6.6	9.1	12.5	14.2
S-A effect		$t(39) = 2.08$, $p = .044$, $d = .33$[a]				$t(39) = 2.47$, $p = .018$, $d = .39$[a]			
S-C effect		$t(39) = 7.99$, $p < .001$, $d = 1.26$[a]				$t(39) = 5.71$, $p < .001$, $d = .90$[a]			
Verbally coded		692	697	700	716	7.4	8.2	10.8	10.0
S-A effect		$t(39) = 2.20$, $p = .034$, $d = .35$[a]				$t(39) = .08$, $p = .940$, $d = .01$			
S-C effect		$t(39) = 2.40$, $p = .022$, $d = .38$[a]				$t(39) = 4.33$, $p < .001$, $d = .68$[a]			

Note. S-A = stimulus–action; S-C = stimulus–classification. RTs and PEs are further displayed as a function of prime type (executed vs. verbally coded), classification (repetition vs. switch), and action (repetition vs. switch). Furthermore, RTs and PEs as well as the test statistics of their respective S-A and S-C effects are displayed separately for prime type, classification, and action.

[a] Significant differences.

showed a nonsignificant trend toward larger PE effects of action switches in executed than verbally coded blocks, $F(1, 38) = 3.30$, $p = .077$, $\eta_p^2 = .08$. All other effects failed to reach significance, $Fs \leq 2.08$, $ps \geq .158$, $\eta_p^2 \leq .05$. Post hoc paired t tests, examining S-A effects separately for the two prime types, showed that action switches were associated with significant PE increase in comparison to action repetitions in executed blocks, $t(39) = 2.47$, $p = .018$, $d = 0.39$, but not in verbally coded blocks, $t(39) = 0.08$, $p = .940$, $d = 0.01$.

Discussion

Experiment 1 explored whether the mere simultaneous presentation of object images and verbal codes denoting class and action induces the formation of S-A and S-C associations even though the corresponding actions are not actually performed. It further explored whether S-A and S-C associations based on verbal codes are automatically retrieved, thus affecting behavior similarly as associations created during task execution.

Item-specific S-A/S-C switches from prime to probe affected probe trial performance for executed and verbally coded primes, indicating that both S-A and S-C associations can be established by single-trial execution as well as by a single trial of verbal coding. When S-C mappings switched rather than repeated between the prime and probe instance of an item, RTs and error rates significantly increased. For switches in S-A mappings, we found significant RT increases and a similar but nonsignificant trend for error rates. These findings indicate that during prime trials both S-A and S-C associations were formed and automatically retrieved in the subsequent probe trials. In line with previous studies (e.g., Moutsopoulou & Waszak, 2012; Moutsopoulou et al., 2015) effects of switches in S-A and S-C mapping did not interact suggesting that S-A and S-C associations are formed and retrieved independently from one another.

Crucially, the described behavioral effects of S-A and S-C switches were present both when participants had actively classified objects by pressing a left/right key during prime trials in executed blocks and when participants had merely attended to the presentation of verbal codes while viewing objects. This demonstrates that S-A as well as S-C associations were formed and retrieved for prime–probe pairs both when associations were formed with action and without action in prime trials. The effects remained stable when checking and controlling for alternative influences of a priori differences and $n - 1$ task switches (see Appendix).

It should be noted that the behavioral effects of verbal codes emerged even though the experiment was explicitly designed to discourage application intentions. That is, during verbally coded primes participants were explicitly told not to respond. Moreover, S-A and S-C mappings did not repeat between prime and probe in 75% of cases (50% S-A switches, 50% S-C switches). The retrieval of primed S-A and S-C mappings was therefore not beneficial to probe performance for the majority of cases. We thus conclude that the coinciding presentation of verbal codes and stimuli lead to the formation of S-R associations that were automatically retrieved without a need for intentions regarding the application of verbally coded S-A and S-C mappings.

In the present experiment, participants were explicitly instructed not to apply verbal codes. Furthermore, verbal codes did not always potentially support later probe trial performance. In contrast, in 75% of the trials, either S-A and/or S-C mapping mismatched between the prime and probe instance of a stimulus. Moreover, the block structure, with separate executed and verbally coded blocks and an announcement of the block type prior to the beginning of the first trial, was installed to prevent participants from accidentally performing responses. However, given that participants always placed their fingers on the keys at the beginning of the block and were prepared to respond to stimuli later on, there
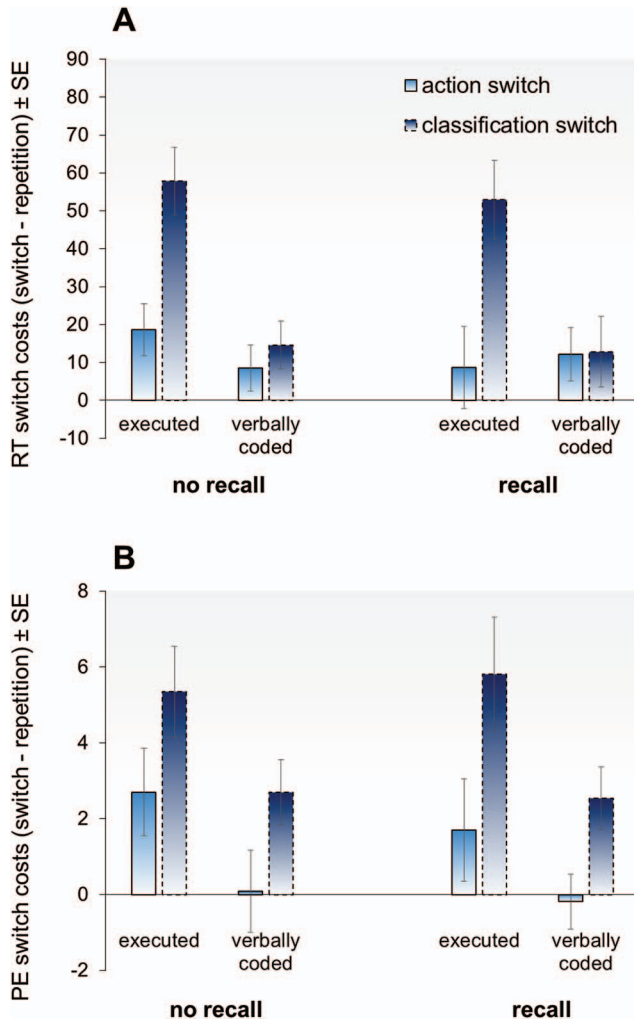
Figure 4. Switch costs (switch—repetition) for action switches and classification switches in Experiment 1. Switch costs for (A) reaction times (RTs) and (B) percentages of errors (PEs) are displayed for the two prime types (executed vs. verbally coded) and the two recall groups (recall vs. no recall). Error bars indicate standard errors of the mean. See the online article for the color version of this figure.

is a possibility that participants performed micromovements or covertly activated responses during a proportion of verbally coded prime trials. Even though in the present experiment we can rule out mental task execution as an alternative explanation (see also Liefooghe et al., 2012; Meiran, Pereg, Kessler, Cole, & Braver, 2015), as no task cue that would have allowed for an imaginary execution of stimulus classification was present during verbally coded prime trials, participants could still have unintentionally performed covert movements on a proportion of trials. Although we strongly discouraged participants from performing movements during verbally coded prime trials, this alternative explanation to the processes underlying verbally coded S-R associations, which also holds true for many prior studies investigating whether instructions are sufficient to establish S-R associations (e.g., Cohen-Kdoshay & Meiran, 2007, 2009; Liefooghe et al., 2012; Meiran et al., 2015), is hard to rule out completely.

Moreover, the behavioral effects of verbally coded S-C associations were significantly smaller than those of executed S-C associations. Conversely, there was no difference between S-A associations formed by execution and by mere verbal coding. These results show that task execution gives rise to stronger S-C (but not S-A) associations with more pronounced behavioral impact.

This finding fits nicely to the notion of transfer appropriate processing (e.g., Morris, Bransford, & Franks, 1977). Because participants' tasks during prime and probe instances are identical in executed blocks, but changes between prime and probe for verbally coded-blocks, differences in the size of the observed effects of execution-based associations and associations based on verbal codes might result from different transfer conditions.

Furthermore, we found that RT and PE switch effects were generally larger for switches in S-C mapping in comparison to switches in S-A mapping. This suggests that across executed and verbally coded mappings, the stimulus representation was more strongly associated with its semantic class than with the motor code of the corresponding action. This finding is in line with previous studies which have demonstrated that S-C associations have stronger behavioral effects and are more reliably observed than S-A associations (e.g., Hsu & Waszak, 2012; Moutsopoulou et al., 2015).

Moreover, the observed increases in RTs and PEs for switches relative to repetitions of the S-A and S-C mapping could have been caused either by facilitatory processes for mapping repetitions, leading to performance benefits, and/or they could have been caused by interference from previously formed associations in the case of mapping switches, leading to performance costs. For executed S-R mappings, a comparison of prime trial and probe trial performance (see Appendix) provided evidence suggestive of a contribution of both facilitation and interference to the observed effects (see also Moutsopoulou et al., 2015, for further evidence of interference from previously executed prime trials). However, as probe trial performance also likely benefited from perceptual priming (e.g., Wiggs & Martin, 1998), making the contribution of facilitatory and interference processes hard to discern, future studies should additionally present new items during probes and compare probe performance for previously primed items to performance for these new items to obtain more direct evidence for both processes of facilitation and interference. The inclusion of new items during probes would also enable the investigation of facilitation and interference for verbally coded stimuli.

Finally, our results indicate that S-A and S-C associations were formed irrespective of whether participants had to memorize prime mappings or not. This is especially remarkable with regards to the effects of nonmemorized verbally coded primes on later behavior. Even when verbal class and action codes were merely presented simultaneously with stimuli without participants acting and without these verbal codes supporting task performance, verbal codes still lead to the formation of S-R associations and affected later behavior.

Taken together, the present findings indicate that both S-R associations formed by task execution as well as by mere verbal codes coinciding with stimulus presentation are composed of two distinct types of associations—S-A and S-C associations. The distinction between two separate S-R associations, a "declarative" task association and a "procedural" action association, also matches the assumed distinction between a declarative and a

procedural working memory, which is regarded as the basis for selecting an object of thought independent from performing manipulations or actions upon it (Oberauer, 2010). Implying that the mere coinciding presentation of verbal codes is sufficient for setting both types of associations, the present findings suggest that automatic processes serving human action control may depend less on task execution, that is, training, than previously thought. Instead stimulus–response associations as the basis of behavioral automatization can also be instantiated by the mere simultaneous presentation of stimuli and verbal codes.

Experiment 2

Previous studies on the temporal stability of executed S-A and S-C associations suggest that S-C associations are more temporally stable than S-A associations (Moutsopoulou & Waszak, 2013). The behavioral effects of previously primed S-C associations, but not S-A associations, can even be traced across hundreds of interleaved trials in RT distributions (Moutsopoulou & Waszak, 2013). These findings have also been taken as evidence for different neuronal pathways underlying the behavioral effects of S-A and S-C associations (Aarts, Roelofs, & van Turennout, 2009; see Moutsopoulou & Waszak, 2013, for a detailed discussion).

Given the differences in temporal stability between different components of S-R associations based on task execution, it is reasonable to assume that associations based on verbal codes may also differ from execution-based associations in terms of their temporal stability. Experiment 1 showed that S-C associations based on verbal codes were generally weaker than executed S-C associations in terms of their behavioral impact. This finding suggests that associations formed by task execution might also be more long-lasting, that is, more temporally stable, than associations formed by verbal codes, which we investigated in Experiment 2.

To investigate the temporal stability of associations formed by mere verbal coding in comparison to associations formed by task execution, we systematically varied the interval between the prime and probe instance of a specific stimulus in four between-subjects groups. The interval between prime and probe instance was either one block, three blocks, seven blocks, or an entire day. Apart from this change the experimental structure remained largely the same as in Experiment 1. In Experiment 2, to ensure participants attended to verbal codes, we asked all participants to try and memorize the presented verbal codes and recall some of them after the respective stimuli had been probed.

Using this paradigm, we hypothesized that execution-based S-C associations should affect behavior even with a temporal delay of several minutes between prime and probe instance, whereas execution-based S-A associations should decay faster and might not show any behavioral effects with prime–probe intervals of several minutes. Moreover, we expected associations based on verbal codes to show a behavioral pattern similar to execution-based associations with relatively temporally stable S-C associations and temporally unstable S-A associations. Nevertheless, S-C associations based on verbal codes should prove less temporally stable than execution-based S-C associations given their initial differences in associative strength.

Method

Participants. Eighty participants were recruited (21 male, 5 left-handed; M_{age} = 23.6 years) and randomly assigned to one of the four prime–probe interval groups (delay between prime and probe instance of an item: one block vs. three blocks vs. seven blocks vs. one day). All participants provided written informed consent prior to participation and none of the participants had to be excluded.

Stimuli and apparatus. Like in Experiment 1, participants sat approximately 60 cm from a 17-in. CRT screen (1,024 pixels × 768 pixels) in a dimly lit, sound-attenuated room. They wore headphones and their index fingers rested on two external keys placed in front of them to the left and right.

Participants performed the same two classification tasks as in Experiment 1 (size vs. mechanism classification) on 448 distinct and easy to classify object images (256 pixels × 256 pixels, about 8° visual angle; 112 per size–mechanism category combination) from the same set by Brady et al. (2008) and Moutsopoulou et al. (2015). Again, each item was only presented twice throughout the experiment, once as a prime and once as a probe. Twenty-four additional object images were used in a preceding practice. As we varied the temporal delay between the prime and the probe instance of an item (one block vs. three blocks vs. seven blocks vs. one day), we used additional items as fillers for probe trials during the first blocks and prime trials during the last blocks of the experiment so that the block structure remained equivalent throughout the course of the experiment. Filler items were excluded from analyses.

The same voice recordings as in Experiment 1 were used during verbally coded prime trials.

Design and procedure. Experiment 2 consisted of 12 practice blocks (six executed, six verbally coded) and 112 blocks in the main experiment (896 trials). Each block randomly featured either executed or verbally coded prime trials (56 blocks each). Four items were randomly chosen as primes of a block, and the instructions as well as trial and block structure equaled Experiment 1. In Experiment 2, primed items were probed with a temporal delay of one block, three blocks, seven blocks, or one day. For instance, in the three-blocks condition, the four items presented as primes in Block 1 were presented as probes in the probe miniblock of Block 4. Therefore, in each block, both executed and verbally coded, four items were primed and four different items were probed. In the temporal delay conditions of one, three, and seven blocks, the block structure was exactly the same as in Experiment 1. In the temporal delay condition of one day, all items were primed in Session 1 and subsequently probed in Session 2, which occurred on the following day at the same time as Session 1. Thus, in this condition, there were prime blocks of four trials each in Session 1 (without probe trials) and probe blocks of four trials each in Session 2 (without prime trials).

To ensure participants attended to the verbal codes, we instructed them to try to memorize the S-A and S-C mappings verbally presented during verbally coded blocks and report them in a memory recall trial which followed the probe miniblock of the respective items (i.e., one block vs. three blocks vs. seven blocks vs. one day later). For each block, one verbally coded prime item of was randomly chosen for memory recall and the structure of the memory recall trial was equivalent to Experiment 1 except that in

Experiment 2 participants had to spell out the item class aloud and then provide the action mapping by pressing the left or right key. Their verbal class responses were recorded for later analysis.

Results

Due to a technical problem with the sound recording, the memory recall data for class were lost for the three last participants in the seven blocks prime–probe interval group. Across all prime–probe intervals, participants responded correctly on 58.4% of class memory recall trials and 55.9% of action memory recall trials. When memory recall was tested after a prime–probe interval of one block, recall rates were 69.1% for class mappings and 61.7% for action mappings, respectively. With a prime–probe interval of three blocks, seven blocks, and one day, respectively, participants correctly recalled 62.6%, 55.8%, and 46.1% of classes and 53.5%, 58.1%, and 50.4% of actions. One sample t tests comparing recall performance to chance showed that, for class recall, performance was above chance level (50%) up to a prime–probe interval of seven blocks, one to seven blocks: $ts \geq 2.35$, $ps \leq .032$, $ds \geq 0.52$, one day: $t(19) = -2.05$, $p = .055$, $d = 0.46$. For action recall, recall performance was above chance for prime–probe intervals one block, three blocks, and one day, $ts \geq 3.35$, $ps \leq .003$, $ds \geq 0.75$, but did not significantly differ from chance at a prime–probe interval of seven blocks, $t(19) = 0.14$, $p = .888$, $d = 0.03$.

RT and PE analyses were conducted as in Experiment 1. The first probe trial of each block was excluded due to the possible influence of the switch from passive listening to active responding in verbally coded blocks. Furthermore, probe error trials (8.7%) as well as probe response omissions (0.5%) were excluded from RT analyses and only items with correct responses in the corresponding prime were used for probe trial RT and PE analyses (5.4% of trials were excluded due to prime trial errors or response omissions). On average, for RT analyses, 13.8% of probe trials were discarded due to these restrictions. Again, RTs deviating from their corresponding cell mean by 3 SD or more were removed from RT analyses (1.1% of the trials). The results for prime trial analyses can be found in the Appendix.

Probe RT analyses. Probe trial RTs were submitted to a 4 × 2 × 2 × 2 mixed-design ANOVA with the between-subjects factor prime–probe interval (one block vs. three blocks vs. seven blocks vs. one day) and the within-subject factors prime type (executed vs. verbally coded), classification (repetition vs. switch), and action (repetition vs. switch). Greenhouse–Geisser corrections were applied where appropriate.

Probe RTs were significantly larger when action, $F(1, 76) = 7.79$, $p = .007$, $\eta_p^2 = .09$, or classification mappings, $F(1, 76) = 64.00$, $p < .001$, $\eta_p^2 = .46$, switched rather than repeated between the prime and probe instance of an item (see Figure 5). Furthermore, both classification, $F(3, 76) = 5.11$, $p = .003$, $\eta_p^2 = .17$, and action, $F(3, 76) = 4.56$, $p = .005$, $\eta_p^2 = .15$, significantly interacted with prime–probe interval. Subsequent paired t tests showed that classification switches were associated with significantly increased RTs in comparison to classification repetitions up to a prime–probe interval of seven blocks, one block: $t(19) = 5.47$, $p < .001$, $d = 1.22$, three blocks: $t(19) = 5.20$, $p < .001$, $d = 1.16$, seven blocks: $t(19) = 4.71$, $p < .001$, $d = 1.05$, one day: $t(19) = 0.56$, $p = .582$, $d = 0.13$. In contrast, the effects of action switches remained significant only for intervals up to three blocks, one

block: $t(19) = 3.78$, $p = .001$, $d = 0.85$, three blocks: $t(19) = 2.44$, $p = .025$, $d = 0.55$, seven blocks: $t(19) = 0.05$, $p = .959$, $d = 0.01$, one day: $t(19) = 0.83$, $p = .420$, $d = 0.18$. Classification significantly interacted with prime type, $F(1, 76) = 6.06$, $p = .016$, $\eta_p^2 = .07$, whereas action did not interact with prime type, $F < 1$. Paired t tests, exploring the interaction of classification and prime type showed that classification switches were associated with significantly larger RTs for both executed, $t(19) = 7.46$, $p < .001$, $d = 0.83$, and verbally coded blocks, $t(19) = 4.17$, $p < .001$, $d = 0.47$; however, the effect of classification switches was significantly larger in executed blocks. Moreover, the three-way interaction between classification, action, and prime–probe interval was significant, $F(3, 76) = 3.13$, $p = .030$, $\eta_p^2 = .11$. Subsequent 2 × 2 repeated-measures ANOVAs with the within-subject factors classification and action, conducted separately for the four prime–probe intervals, revealed that classification and action did not interact at a prime–probe interval of one block or one day, $Fs < 1$, but showed a nonsignificant trend in the three blocks delay condition, $F(1, 19) = 4.10$, $p = .057$, $\eta_p^2 = .18$, and significantly interacted in the seven blocks delay condition, $F(1, 19) = 6.79$, $p = .017$, $\eta_p^2 = .26$. The interaction of prime type, action, and classification did not reach significance, $F(1, 76) = 2.84$, $p = .096$, $\eta_p^2 = .04$. But, we observed a significant main effect of prime type, $F(1, 76) = 79.41$, $p < .001$, $\eta_p^2 = .51$, resulting from overall larger RTs in verbally coded blocks. Prime type significantly interacted with prime–probe interval, $F(3, 76) = 6.44$, $p = .001$, $\eta_p^2 = .20$. Two separate univariate ANOVAs with the factor prime type showed that the main effect of prime–probe interval failed to reach significance for both executed, $F < 1$, and verbally coded blocks, $F(3, 76) = 1.17$, $p = .329$, $\eta_p^2 = .04$. The significant interaction emerged as the course of RTs across prime–probe intervals differed between executed and verbally coded blocks. Furthermore, probe RTs did not differ between prime–probe intervals, $F < 1$. All other effects failed to approach significance, $Fs < 1$. Post hoc paired t tests investigating S-A effects separately for the two prime types revealed that across prime–probe intervals RTs for action switches and action repetitions significantly differed in executed blocks, $t(79) = 2.22$, $p = .030$, $d = 0.25$, but not in verbally coded blocks, $t(79) = 1.51$, $p = .136$, $d = 0.17$. Detailed results and test statistics for specific S-A and S-C effects can be found in Table 2.

Probe error trial analyses. Just like probe RTs, probe PEs were submitted to a 4 × 2 × 2 × 2 mixed-design ANOVA with the between-subjects factor prime–probe interval and the within-subject factors prime type, classification, and action. Greenhouse–Geisser corrections were applied where appropriate. Probe trial PE analysis showed significant main effects of both classification, $F(1, 76) = 67.25$, $p < .001$, $\eta_p^2 = .47$, and action, $F(1, 76) = 6.08$, $p = .016$, $\eta_p^2 = .07$. Both switches in S-C and S-A mapping were associated with higher error rates. Moreover, classification significantly interacted with prime–probe interval, $F(3, 76) = 5.42$, $p = .002$, $\eta_p^2 = .18$. Subsequent paired t tests showed that classification switches were associated with higher error rates compared to classification repetitions up to an interval of seven blocks between prime and probe instance, one block: $t(19) = 4.38$, $p < .001$, $d = 0.98$, three blocks: $t(19) = 6.54$, $p < .001$, $d = 1.46$, seven blocks: $t(19) = 6.32$, $p < .001$, $d = 1.41$, one day: $t(19) = 0.60$, $p = .555$, $d = 0.13$. In contrast, action did not significantly interact with prime–probe interval, $F(3, 76) = 1.37$, $p = .257$, $\eta_p^2 = .05$.
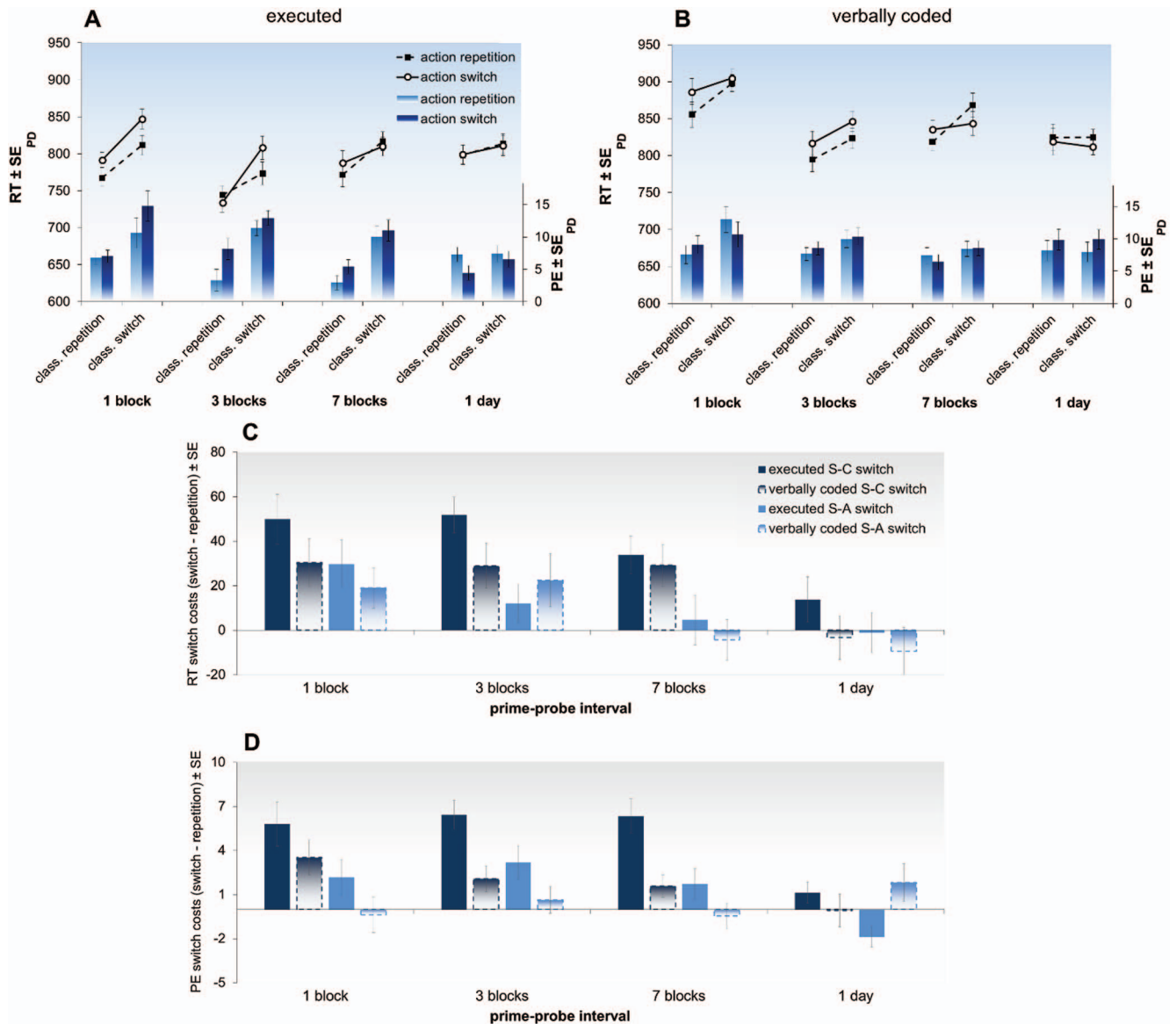
Figure 5. Main results of Experiment 2. Panel A and B show mean reaction times (RTs, in ms; lines) and percentages of errors (PEs, in %; bars) in the probe trials displayed separately for (A) executed and (B) verbally coded primes across the four possible switch conditions (classification: repetition vs. switch; action: repetition vs. switch) and the four prime–probe intervals (one block vs. three blocks vs. seven blocks vs. one day). Error bars indicate standard errors of paired differences (Pfister & Janczyk, 2013) that were computed separately for each classification switch condition. Switch costs (switch—repetition) for (C) RTs and (D) PEs are displayed for the two prime types (executed vs. verbally coded), two switch types (action vs. classification), and four prime–probe intervals (one block vs. three blocks vs. seven blocks vs. one day). Error bars indicate standard errors of the mean. See the online article for the color version of this figure.

Additionally, there was a significant three-way interaction between action, prime type, and prime–probe interval, $F(3, 76) = 3.63$, $p = .017$, $\eta_p^2 = .13$. Subsequent paired t tests showed that action switches only lead to significant increases in error rate in executed blocks and only when the prime–probe interval was three blocks or one day, executed: one block: $t(19) = 1.73$, $p = .101$, $d = 0.39$, three blocks: $t(19) = 2.79$, $p = .012$, $d = 0.62$, seven blocks: $t(19) = 1.65$, $p = .115$, $d = 0.37$, one day: $t(19) = 2.59$, $p = .018$,

$d = 0.58$; verbally coded: ts ≤ 1.44, ps $\geq .167$, ds ≤ 0.58. The three-way interaction of classification, prime type, and prime–probe interval failed to reach significance, $F(3, 76) = 1.52$, $p = .216$, $\eta_p^2 = .06$, whereas the interaction between classification and prime type reached significance, $F(1, 76) = 21.09$, $p < .001$, $\eta_p^2 = .22$. Subsequent paired t tests showed that the classification switches as compared to repetitions were associated with significantly higher error rates for both executed, $t(79) = 8.36$, $p < .001$,

Table 2

Probe Trial Reaction Times (RTs, in ms) and Percentages of Errors (PEs, in %) in Experiment 2 Displayed Separately for the Four Prime-Probe Intervals (One Block vs. Three Blocks vs. Seven Blocks vs. one Day), Prime Type (Executed vs. Verbally Coded), Classification (Repetition vs. Switch), and Action (Repetition vs. Switch)

| | | RTs | | | | PEs | | | |
| | | Classification repetition | | Classification switch | | Classification repetition | | Classification switch | |
Prime-probe interval	Prime type	Action repetition	Action switch	Action repetition	Action switch	Action repetition	Action switch	Action repetition	Action switch
One block	Executed	767	792	812	847	6.8	7.0	10.6	14.8
	S-A effect	$t(19) = 2.91, p = .009, d = .65^a$				$t(19) = 1.73, p = .101, d = .39$			
	S-C effect	$t(19) = 4.30, p < .001, d = .96^a$				$t(19) = 4.07, p = .001, d = .91^a$			
	Verbally coded	856	887	898	905	7.5	9.1	13.0	10.7
	S-A effect	$t(19) = 2.23, p = .038, d = .50^a$				$t(19) = .30, p = .769, d = .07$			
	S-C effect	$t(19) = 2.89, p = .009, d = .65^a$				$t(19) = 2.97, p = .008, d = .66^a$			
Three blocks	Executed	744	734	774	808	3.3	8.1	11.4	12.9
	S-A effect	$t(19) = 1.28, p = .218, d = .29$				$t(19) = 2.79, p = .012, d = .62^a$			
	S-C effect	$t(19) = 6.09, p < .001, d = 1.36^a$				$t(19) = 6.98, p < .001, d = 1.56^a$			
	Verbally coded	795	817	823	846	7.6	8.5	10.0	10.4
	S-A effect	$t(19) = 1.90, p = .073, d = .42$				$t(19) = .70, p = .490, d = .16$			
	S-C effect	$t(19) = 2.94, p = .008, d = .66^a$				$t(19) = 2.36, p = .029, d = .53^a$			
Seven blocks	Executed	772	788	817	810	2.9	5.4	10.0	11.0
	S-A effect	$t(19) = .38, p = .705, d = .09$				$t(19) = 1.65, p = .115, d = .37$			
	S-C effect	$t(19) = 4.40, p < .001, d = .98^a$				$t(19) = 5.47, p < .001, d = 1.22^a$			
	Verbally coded	819	835	869	843	7.4	6.4	8.4	8.5
	S-A effect	$t(19) = .33, p = .749, d = .07$				$t(19) = .51, p = .614, d = .11$			
	S-C effect	$t(19) = 3.11, p = .006, d = .69^a$				$t(19) = 2.20, p = .041, d = .49^a$			
One day	Executed	799	799	814	811	7.3	4.4	7.4	6.5
	S-A effect	$t(19) = .21, p = .838, d = .05$				$t(19) = 2.59, p = .018, d = .58^a$			
	S-C effect	$t(19) = 1.26, p = .222, d = .28$				$t(19) = 1.61, p = .125, d = .36$			
	Verbally coded	825	819	825	812	8.2	9.9	8.0	9.9
	S-A effect	$t(19) = .82, p = .425, d = .18$				$t(19) = 1.44, p = .167, d = .32$			
	S-C effect	$t(19) = .37, p = .719, d = .08$				$t(19) = .09, p = .930, d = .02$			

Note. S-A = stimulus–action; S-C = stimulus–classification. Test statistics of the respective S-A and S-C effects are displayed below the corresponding means.
[a] Significant differences.

$d = 0.93$, and verbally coded blocks, $t(79) = 3.50, p = .001, d = 0.39$. However, the increase in error rates due to classification switches was significantly more pronounced in executed blocks. Moreover, we found a significant four-way interaction between prime type, prime–probe interval, classification, and action, $F(3, 76) = 3.02, p = .035, \eta_p^2 = 11$. Subsequent $2 \times 2 \times 4$ repeated-measures ANOVAs with the within-subjects factors classification and action and the between-subjects factor prime–probe interval conducted separately for the prime types executed and verbally coded revealed that the three-way interaction of classification, action, and prime–probe interval showed a nonsignificant trend in executed blocks, $F(3, 76) = 2.52, p = .064, \eta_p^2 = .09$, and did not approach significance in verbally coded blocks, $F(3, 76) = 1.39, p = .253, \eta_p^2 = .05$. Furthermore, verbally coded blocks were associated with significantly higher error rates than executed blocks, $F(1, 76) = 5.36, p = .023, \eta_p^2 = .07$. There was a trend toward an interaction between prime type and prime–probe interval, $F(3, 76) = 2.52, p = .064, \eta_p^2 = .09$. All other effects failed to reach significance, $Fs \leq 1.52, ps \geq .216, \eta_p^2 \leq .06$. Post hoc t tests investigating the S-A effects separately for the two prime types showed that across prime–probe intervals action switches were only associated with larger PEs as compared to action repetitions in executed blocks, $t(79) = 2.32, p = .023, d = 0.26$. PEs did not significantly differ in verbally coded blocks, $t(79) = 0.78, p = .440, d = 0.09$.

Discussion

Experiment 2 explored the temporal stability of S-A and S-C associations created by task execution and by verbal coding. The only essential difference to Experiment 1 was that primes were probed after a prime–probe interval of one block, three blocks, seven blocks, or one day.

Again, we found that both item-specific switches in S-A mapping and item-specific switches in S-C mapping between prime and probe lead to RT and PE increases, suggesting that both S-A and S-C associations had been formed during prime trials and were automatically retrieved during probe trials. The behavioral effects of both S-A and S-C switches decreased with increasing prime–probe intervals, but effects remained significant even after several blocks between prime and probe. In contrast to the findings of Moutsopoulou and Waszak (2013) both S-A and S-C associations were relatively stable over time with S-C associations being more temporally stable than S-A associations. Crucially, both associations based on task execution and associations based on verbal codes exhibited similar temporal stability.

The finding that not only execution-based associations, but also associations based on the simultaneous presentation of verbal codes are temporally stable is interesting, because it shows that neither execution-based associations nor associations based on verbal codes can rely solely on working memory representations.

To show an effect after three or even seven blocks, participants would need to hold a large number of items in memory, most likely exceeding the well-known capacity limitation of working memory. This suggests that in contrast to instruction-based effects (Meiran et al., 2012), effects of verbal codes are automatic in the sense that they do not rely on working memory capacity.

Experiment 3

To further assess potential differences between execution-based associations and associations based on verbal codes, Experiment 3 aimed at comparing the resilience of S-A and S-C associations instantiated by task execution and by mere verbal codes against being overwritten by competing associations. We explored how many relearning instances were necessary to counteract the behavioral effects of a single executed or verbally coded prime instance. To be precise, we assessed after how many probe instances RT and PE increases for S-A and S-C switches did not differ from S-A and S-C repetitions any more. Based on the finding that both execution-based S-A and S-C associations exert behavioral effects across several probe presentations (Moutsopoulou et al., 2015), we compared S-A and S-C associations instantiated by task execution and by verbal codes in terms of their resilience across four probe presentations. Given the findings of Moutsopoulou et al. (2015), we expected S-C associations to be more resilient than S-A associations. Additionally, we expected associations created by task execution to be generally more resilient than associations created by verbal codes.

Method

Participants. Forty participants (12 male, two left-handed; M_{age} = 24.0 years) took part and provided written informed consent. One of the participants had to be excluded as more than 50% of that participant's probe trial data had to be excluded due to errors and response omissions in the probe trials or corresponding prime trials.

Stimuli and apparatus. Again, participants sat approximately 60 cm from a 17-in. CRT screen (1,024 pixels × 768 pixels) in a dimly lit, sound-attenuated room. They wore headphones and their index fingers rested on two external keys placed in front of them to the left and right.

Participants performed size and mechanism classifications on 448 distinct and easy to classify object images (256 pixels × 256 pixels, about 8° visual angle; 112 per size–mechanism category combination) from the same set by Brady et al. (2008) and Moutsopoulou et al. (2015). Twenty-four additional object images were used in a preceding practice. The same voice recordings as in Experiment 1 were used during verbally coded prime trials.

Design and procedure. As the duration of the experiment was substantially increased due to the multiple probes, the study was conducted in two sessions of about 1 hr each. The second session took place within a week from the first session and half of the items were primed and probed in Session 1 and 2, respectively.

The block and trial structure were the same as in Experiment 1 with the exception that items were presented once as a prime and four times as a probe, leading to a prime miniblock of four trials and four subsequent probe miniblocks of four trials each. Importantly, S-A and S-C mappings independently repeated or switched

between the prime instance and the first probe instance of an item. For subsequent probe instances, S-A and S-C mappings remained the same as during the first probe instance, so that the relationship between the prime instance and all four probe instances of a specific item remained constant (full repetition, action switch, classification switch, or full switch). The same item was never presented on two successive trials.

To enhance attention especially to the verbal codes and increase the chance of finding resilient priming effects across several probe instances, we introduced memory recall trials for both verbally coded and executed blocks. In Experiment 3, we had participants recall the S-A and S-C mapping of all four primed items to get a more reliable estimate of their prime trial memory.

Results

RT and PE analyses were conducted as in Experiment 1. The first probe trial of each block was excluded. Probe error trials (7.7%) as well as probe response omissions (0.8%) were excluded from RT analyses. Additionally, only items with correct responses in the corresponding prime (6.2% errors and 1.1% response omissions) and all preceding probe instances were used for probe trial RT and PE analyses. Due to these restrictions, on average 25.8% of probe trials were excluded from RT analyses. Finally, RTs deviating from their corresponding cell mean by 3 SD or more were removed from RT analyses (1.1% of the trials).

Overall, participants responded correctly on 64.5% of class memory recall trials (executed: 61.2%, verbally coded: 67.8%) and 61.8% of action memory recall trials (executed: 57.1%, verbally coded: 66.4%). One sample t tests showed that participants performance was significantly above chance (50%) for both class and action recall both in executed and verbally coded blocks, ts ≥ 4.71, ps ≤ .001, ds ≥ 0.74. The results for prime trial analyses can be found in the Appendix.

Probe RT analyses. We conducted a 4 × 2 × 2 × 2 repeated-measures ANOVA on probe trial RTs with the within-subject factors probe instance (1–4), prime type (executed vs. verbally coded), classification (repetition vs. switch), and action (repetition vs. switch). Greenhouse–Geisser corrections were applied where appropriate. Classification and action switches were defined as item-specific switches between the prime of an item and its corresponding four probes.

We found both a significant main effect of classification, $F(1, 38) = 64.45$, $p < .001$, $\eta_p^2 = .63$, and action, $F(1, 38) = 10.63$, $p = .002$, $\eta_p^2 = .22$. Switches in classification or action mapping were associated with significantly slower RTs (see Figure 6 and Table 3 for detailed results). Moreover, classification significantly interacted with prime type, $F(1, 38) = 9.04$, $p = .005$, $\eta_p^2 = .19$, whereas action did not, $F(1, 38) = 2.90$, $p = .097$, $\eta_p^2 = .07$. Subsequent paired t tests showed that classification switches were associated with significantly slower RTs in both executed, $t(38) = 7.24$, $p < .001$, $d = 1.16$, and verbally coded blocks, $t(38) = 5.03$, $p < .001$, $d = 0.80$. However, the RT increase associated with classification switches was significantly more pronounced in executed than verbally coded blocks. Furthermore, classification significantly interacted with probe instance, $F(1, 38) = 9.15$, $p < .001$, $\eta_p^2 = .19$. Paired t tests showed that RTs for classification switches were significantly larger than RTs for classification repetitions for all four probe instances, Probe Instance 1: $t(38) = 7.22$,
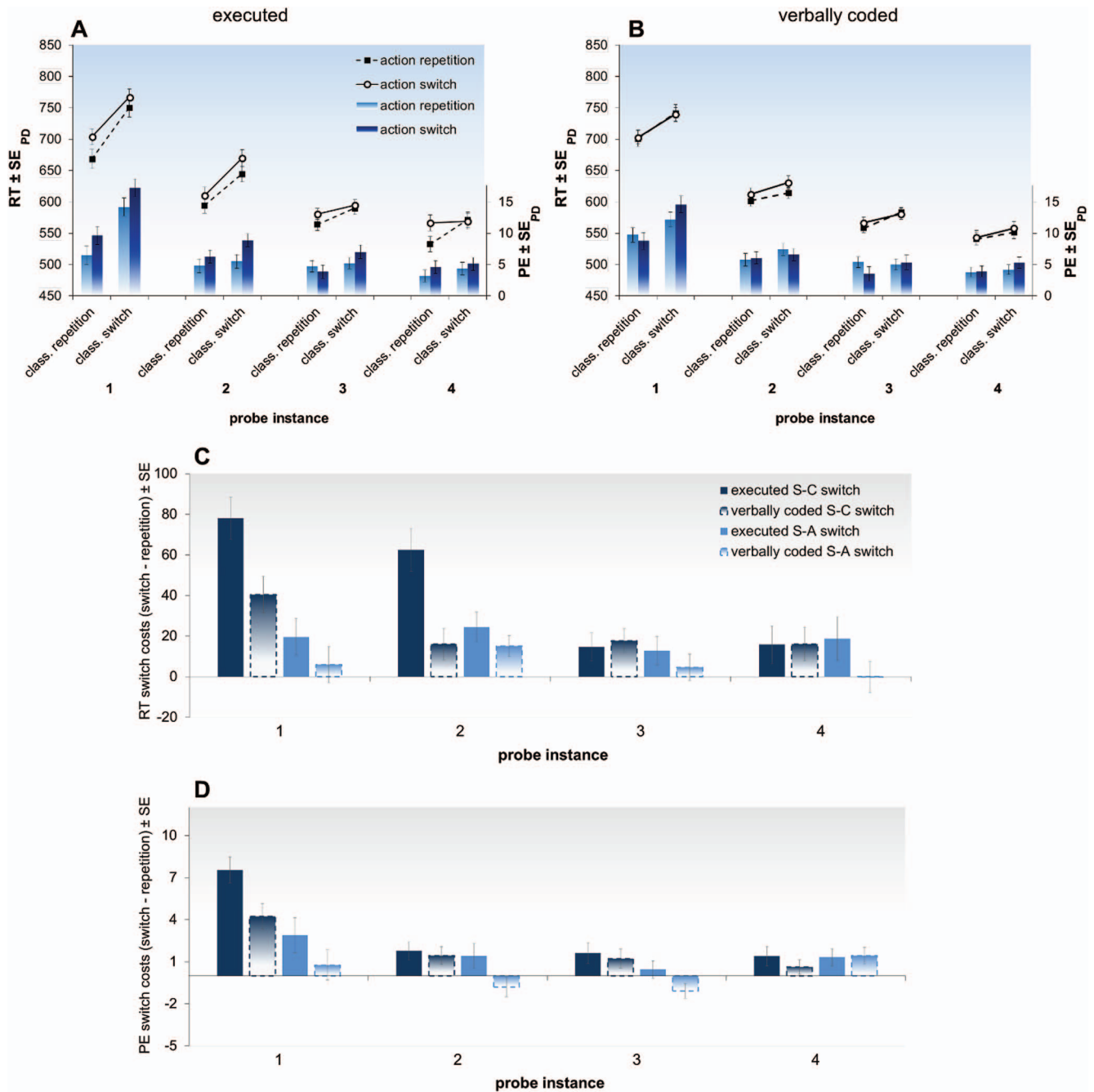
Figure 6. Main results of Experiment 3. Panel A and B show mean reaction times (RTs, in ms; lines) and percentages of errors (PEs, in %; bars) in the probe trials displayed separately for (A) executed and (B) verbally coded primes across the four possible switch conditions (classification: repetition vs. switch; action: repetition vs. switch) and the four probe instances. Error bars indicate standard errors of paired differences (Pfister & Janczyk, 2013) that were computed separately for each classification switch condition. Switch costs (switch—repetition) for (C) RTs and (D) PEs are displayed for the two prime types (executed vs. verbally coded), two switch types (action vs. classification), and four prime repetitions. Error bars indicate standard errors of the mean. See the online article for the color version of this figure.

$p < .001$, $d = 1.16$; Probe Instance 2: $t(38) = 5.12$, $p < .001$, $d = 0.82$; Probe Instance 3: $t(38) = 3.61$, $p = .001$, $d = 0.58$; Probe Instance 4: $t(38) = 2.89$, $p = .006$, $d = 0.46$. Yet, the RT increase associated with a classification switch was most pronounced at the

first probe presentation and declined across probe instances. The interaction between classification and probe instance was further qualified by a three-way interaction between classification, probe instance, and prime type, $F(1, 38) = 3.26$, $p = .031$, $\eta_p^2 = .08$.

Table 3

Probe Trial Reaction Times (RTs, in ms) and Percentages of Errors (PEs, in %) in Experiment 3, Displayed Separately for the Four Probe Instances

		RTs				PEs			
		Classification repetition		Classification switch		Classification repetition		Classification switch	
Probe instances	Prime type	Action repetition	Action switch	Action repetition	Action switch	Action repetition	Action switch	Action repetition	Action switch
1	Executed	668	704	750	767	6.5	9.6	14.2	17.2
	S-A effect	$t(38) = 3.05, p = .004, d = .49$[a]				$t(38) = 2.56, p = .015, d = .41$[a]			
	S-C effect	$t(38) = 7.00, p < .001, d = 1.12$[a]				$t(38) = 8.40, p < .001, d = 1.34$[a]			
	Verbally coded	701	703	742	740	9.7	8.8	12.2	14.6
	S-A effect	$t(38) = .01, p = .991, d = .00$				$t(38) = .62, p = .540, d = .10$			
	S-C effect	$t(38) = 4.23, p < .001, d = .68$[a]				$t(38) = 4.70, p < .001, d = .75$[a]			
2	Executed	594	610	645	670	4.8	6.2	5.5	8.9
	S-A effect	$t(38) = 2.92, p = .006, d = .47$[a]				$t(38) = 2.66, p = .011, d = .43$[a]			
	S-C effect	$t(38) = 5.20, p < .001, d = .83$[a]				$t(38) = 2.46, p = .019, d = .39$[a]			
	Verbally coded	602	612	614	631	5.8	6.0	7.4	6.6
	S-A effect	$t(38) = 2.57, p = .014, d = .41$[a]				$t(38) = .34, p = .740, d = .05$			
	S-C effect	$t(38) = 2.01, p = .052, d = .32$				$t(38) = 1.72, p = .093, d = .28$			
3	Executed	564	581	590	595	4.7	3.8	5.2	7.0
	S-A effect	$t(38) = 1.67, p = .105, d = .27$				$t(38) = .56, p = .576, d = .09$			
	S-C effect	$t(38) = 2.92, p = .006, d = .47$[a]				$t(38) = 2.42, p = .020, d = .39$[a]			
	Verbally coded	558	567	584	581	5.4	3.5	5.0	5.3
	S-A effect	$t(38) = .41, p = .686, d = .07$				$t(38) = 1.66, p = .106, d = .27$			
	S-C effect	$t(38) = 3.19, p = .003, d = .51$[a]				$t(38) = 1.03, p = .311, d = .16$			
4	Executed	533	566	572	569	3.1	4.6	4.4	5.1
	S-A effect	$t(38) = 1.64, p = .109, d = .26$				$t(38) = 1.61, p = .117, d = .26$			
	S-C effect	$t(38) = 2.49, p = .017, d = .40$[a]				$t(38) = 1.20, p = .237, d = .19$[a]			
	Verbally coded	541	543	551	558	3.8	3.9	4.2	5.3
	S-A effect	$t(38) = .67, p = .506, d = .11$				$t(38) = .84, p = .407, d = .13$			
	S-C effect	$t(38) = 1.60, p = .119, d = .26$				$t(38) = 1.75, p = .089, d = .28$			

Note. S-A = stimulus–action; S-C = stimulus–classification. RTs and PEs are further displayed as a function of prime type (executed vs. verbally coded), classification (repetition vs. switch), and action (repetition vs. switch). Furthermore, test statistics of the respective S-A and S-C effects are displayed below the corresponding means.
[a] Significant differences.

Paired *t* tests exploring this interaction showed that RT increases associated with classification switches were significant for all four probe instances in executed blocks, $t(38) \geq 2.49, p \leq .017, d \geq 0.40$, but only reached significance for probe instance one and three in verbally coded blocks, Probe Instance 1: $t(38) = 4.23, p < .001, d = 0.68$; Probe Instance 2: $t(38) = 2.01, p = .052, d = 0.32$; Probe Instance 3: $t(38) = 3.19, p = .003, d = 0.51$; Probe Instance 4: $t(38) = 1.60, p = .119, d = 0.26$. Moreover, the main effect of probe instance was significant, $F(1, 38) = 143.01, p < .001, \eta_p^2 = .79$, with RTs decreasing across probe instances. All other effects failed to reach significance, $Fs \leq 2.54, p \geq .120, \eta_p^2 \leq .06$. Post hoc paired *t* tests conducted to investigate S-A effects separately for executed and verbally coded blocks showed that across all four probe instances action switches were only associated with significantly higher RTs than action repetitions in executed blocks, $t(38) = 3.65, p = .001, d = 0.58$, but not in verbally coded blocks, $t(38) = 1.19, p = .241, d = 0.19$. Detailed results for specific S-C and S-A effects can be found in Table 3.

Probe error trial analyses. Probe PE analyses, in parallel with the RT analysis, were conducted by means of a $4 \times 2 \times 2 \times 2$ repeated-measures ANOVA with the within-subject factors probe instance, prime type, classification, and action. Greenhouse–Geisser corrections were applied where appropriate.

In parallel with the RT analysis, the PE analysis showed that both switches in classification mapping, $F(1, 38) = 53.88, p < .001, \eta_p^2 = .59$, and switches in action mapping, $F(1, 38) = 7.71, p = .008, \eta_p^2 = .17$, between prime and probe were associated with significant error rate increases. Both classification, $F(1, 38) = 6.94, p = .012, \eta_p^2 = .16$, and action, $F(1, 38) = 8.95, p = .005, \eta_p^2 = .19$, significantly interacted with prime type. However, as subsequent paired *t* tests revealed, whereas there were classification switch effects for both executed, $t(38) = 7.05, p < .001, d = 1.13$, and verbally coded blocks, $t(38) = 4.37, p < .001, d = 0.70$, the error rate increase associated with action switches was only significant in executed blocks, $t(38) = 3.47, p = .001, d = 0.56$, and failed to reach significance in verbally coded blocks, $t(38) = 0.05, p = .958, d = 0.01$. Additionally, classification and action showed a nonsignificant trend toward an interaction, $F(1, 38) = 3.53, p = .068, \eta_p^2 = .09$. Finally, error rates significantly decreased across probe instances, $F(1, 38) = 114.76, p < .001, \eta_p^2 = .75$, and similarly the error rate increases associated with classification switches rather than repetitions reduced across probe instances, $F(1, 38) = 29.06, p < .001, \eta_p^2 = .43$; Probe Instance 1: $t(38) = 10.76, p < .001, d = 1.72$; Probe Instance 2: $t(38) = 2.67, p = .011, d = 0.43$; Probe Instance 3: $t(38) = 2.28, p = .028, d = 0.36$; Probe Instance 4: $t(38) = 2.03, p = .049, d = 0.33$. All other effects failed to reach significance, $Fs \leq 1.96, p \geq .124, \eta_p^2 \leq .05$. Post hoc *t* test examining the difference between action switches and action repetitions for the two prime types showed that, across the four probe instances, participants committed significantly more

errors for action switches in comparison to action repetitions in executed blocks, $t(38) = 3.47$, $p = .001$, $d = 0.56$, but not in verbally coded blocks, $t(38) = 0.05$, $p = .958$, $d = 0.01$.

Discussion

In Experiment 3, we compared the resilience of S-A and S-C associations based on task execution and mere verbal codes. In both executed and verbally coded blocks, stimuli occurred once as a prime and four times as a probe. During prime instances, participants either actively classified the stimuli or passively attended to a verbally presented S-A and S-C mapping. In probe trials, participants always actively classified stimuli by pressing a left or right key in accordance with a preceding cue. Between prime and probe instance both S-A and S-C mappings could either repeat or switch. S-A and S-C mappings chosen for the first probe of an item consistently repeated for the following three probe instances of the same item, so that the relation between the prime instance of a specific item and its subsequent probe instances remained constant (full repetition, action switch, classification switch, full switch).

Our findings demonstrate that both S-A and S-C associations were formed during prime trials and subsequently affected participants′ behavior during probe trials. Prime trial S-C mappings continued to affect RTs and PEs even during the fourth probe instance. Significant S-A effects were only present during the first two probes. Most interestingly, whereas execution-based S-C associations were still traceable during the fourth probe instance, the effects of S-C associations based on verbal codes were less resilient and disappeared after the third probe instance.

Nonetheless, however, associations based on verbal codes were detectable across several relearning instances. This finding underlines that, like execution-based associations, associations based on verbal codes were automatically retrieved. Thus, in contrast to instruction-based effects, the behavioral effects of associations based on verbal codes are not based on plan-to-execution events that are only active until a plan/goal has been realized.

Taken together, the findings of Experiment 3 indicate that both execution-based associations and associations based on verbal codes are relatively resilient and are only revoked after several relearning instances. This is especially remarkable given that prime S-A and S-C mappings only matched probe mappings in 25% of the trials, whereas probe mappings repeated four times, meaning that the encoding and later retrieval of primed mappings was not advantageous to performance. These results further support the notion that both active task execution and passive attendance to verbal codes leads to the formation of resilient, automatic S-R associations.

General Discussion

In three item-specific priming experiments using an object classification task, we tested whether automatic S-R associations are formed even in the absence of action, that is, when stimuli are presented simultaneously with verbal codes regarding stimulus classifications and actions. Just like for the formation of execution-based associations (e.g., Moutsopoulou et al., 2015), a single prime trial without action was sufficient to establish S-R associations. Our findings further demonstrate that associations created by verbal codes were also similarly temporally stable and resilient against overwriting as execution-based associations.

Furthermore, we were able to decompose S-R associations into S-A and S-C associations for both S-R associations instantiated by active task execution and by passively listening to verbal codes. The existence of these two distinct components of S-R associations is thought to enable behavioral flexibility, as S-C associations create an action context detached from the specific response associated with a stimulus (Abrams, Klinger, & Greenwald, 2002), thus allowing for more adaptive stimulus-driven behavior depending on the task at hand. Interestingly, this study as well as previous studies (Moutsopoulou & Waszak, 2012, 2013; Moutsopoulou et al., 2015) have consistently found evidence for the independent retrieval of S-A and S-C associations, indicating that S-A and S-C associations are not (or not only) organized into hierarchical task-set representations, but are formed and retrieved separately independently of each other.

As pointed out in the discussion of Experiment 1, covert response activation during verbally coded prime trials cannot be ruled out completely with the present paradigm. However, given that we strongly discouraged participants from accidental task execution during verbally coded prime trials, we believe that covert response activation might contribute to the observed effects, but is unlikely to be their main source. Nevertheless, future studies should aim to further investigate micromovements and covert response activation as factors possibly contributing to verbally coded S-R associations and elaborate on whether verbally coded S-R associations are truly formed in the absence of action or only in the absence of action intention.

Most importantly, however, we provide clear evidence that the active, intentional execution of a task is not necessary for automatically retrievable S-R associations to emerge. Instead, verbal codes specifying stimulus classes and actions simultaneously presented with an object image are sufficient for both automatic S-A and S-C associations to be created. Given that these associations based on verbal codes were created even though participants were not instructed to apply the presented information and given that S-A and S-C mappings between prime and probe switched in 75% of the trials, making the formation and retrieval of S-R associations not beneficial to performance in most cases, it is evident that the observed effects do not depend on an intentional retrieval of primed mappings. Furthermore, the findings of Experiment 2 and 3 showing that both execution-based associations and associations based on verbal codes are temporally stable and resilient, indicate that the observed associations based on verbal codes can neither rely on working memory capacity nor be based on plan-to-execution events. Thus, the associations based on verbal codes we report are not bound by any of the three prerequisites of instruction-based effects (working memory capacity, intention, integration in a plan-to-execution event), but like execution-based associations are automatic in nature such that they operate without intention or working memory resources.

In conclusion, we demonstrate that S-R associations can be formed in the absence of action. The mere simultaneous presentation of verbal codes with stimuli was sufficient for establishing automatic, temporally stable, and resilient S-R associations. These findings show that the presence of verbal codes in the absence of task execution is sufficient for stimuli and verbally coded response components to bind together and for the resulting S-R associations to lead to automatic S-R translation when stimuli are reencountered. Thus, we demonstrate that behavioral automaticity is even

broader than previously conceptualized and can be achieved in the absence of action, extending classical theories of S-R binding and pointing toward the striking adaptability of human action control.

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Appendix

The Power of Words – Further Analyses

Experiment 1

Prime analyses.

Prime RT and PE results. Validation analyses in terms of $2 \times 2 \times 2$ mixed-design ANOVAs with the between-subjects factor memory recall group (recall vs. no recall) and the within-subjects factors classification (repetition vs. switch) and action (repetition vs. switch) were conducted on *executed prime* trial RTs and PEs to test for a priori differences between trials with later repetitions versus switches in later prime–probe action and/or classification mapping. These analyses did not yield any significant main effects of action or classification. RTs: $Fs \leq 1$, PEs: $Fs \leq 2.69$, $p \geq .109$, $\eta_p^2 \leq .07$. However, prime RTs were significantly shorter in the no recall group in comparison to the recall group, $F(1, 38) = 8.23$, $p = .007$, $\eta_p^2 = 18$. For PEs, there was a significant interaction between classification and memory recall group, $F(1, 38) = 5.72$, $p = .022$, $\eta_p^2 = 13$. Classification switches were associated with fewer errors than classification repetitions in the recall group, $t(19) = 2.37$, $p = .029$, $d = .53$, whereas PEs in the no recall group did not show a significant difference, $t(19) = 0.73$, $p = .472$, $d = .16$. All other effects failed to reach significance, RTs: $Fs \leq 1.53$, $p \geq .224$, $\eta_p^2 \leq .04$, PEs: $Fs < 1$.

Discussion. The absence of main effects of classification and action as well as interactions of these factors suggests that there were no differences between classification and action switch conditions in the prime trials ruling out a priori differences between conditions. Interestingly, RTs in the prime trials of the no recall group were generally faster than in the recall group's prime trials. This finding can most likely be attributed to the fact that memorization of the executed

action and classification mappings in the recall group introduced a secondary task, thus increasing overall RTs. Finally, we found an interaction between classification and memory recall group in error rates. At present we do not have an explanation for this finding, given that participants could not have known about the classification mapping of the later probe trials. We therefore believe this finding to represent a Type I error rather than an actual effect.

n − 1 task switches. Separate paired *t* tests for RTs and PEs revealed significant task switching effects in RTs, $t(39) = 5.01$, $p < .001$, $d = .79$, with faster RTs for task repetitions than task switches in relation to the immediately preceding trial (Trial $n − 1$). For PEs, the effect of task switches failed to reach significance, $t(39) = 1.41$, $p = .168$, $d = .22$.

To account for the possible influence of $n − 1$ task switches on effects of item-specific switches between prime and probe, we conducted another $2 \times 2 \times 2 \times 2$ mixed-design ANOVA with the factors memory recall group, prime type, action, and classification, using the residuals of a regression with RT as criterion and $n − 1$ task switch (repetition vs. switch) as predictor as dependent variable.

This RT analysis cleared from the effects of task switches between trial $n − 1$ and trial n revealed significant main effects of both action, $F(1, 38) = 7.04$, $p = .012$, $\eta_p^2 = .16$, and classification, $F(1, 38) = 46.10$, $p < .001$, $\eta_p^2 = .55$, with larger RT residuals being associated with switches in action and classification, respectively (see Table A1). The main effect of prime type showed a nonsignificant trend toward larger RT residuals in executed blocks, $F(1, 38) = 3.87$, $p = .056$, $\eta_p^2 = .09$. Furthermore,

(Appendix continues)

Table A1

Residuals of the Probe Trial Reaction Times (RTs) of Experiment 1 Displayed Overall as Well as Separately for the Two Memory Recall Groups (No Recall vs. Recall)

| Memory recall group | Prime type | RT residuals | | | |
| | | Classification repetition | | Classification switch | |
		Action repetition	Action switch	Action repetition	Action switch
Overall	Executed	−36.52	−16.11	26.74	28.80
	Verbally coded	−8.89	−4.71	−1.42	13.61
No recall	Executed	−38.00	−15.59	23.57	34.83
	Verbally coded	−13.35	−.42	4.85	8.53
Recall	Executed	−35.05	−16.63	29.91	22.78
	Verbally coded	−4.44	−9.00	−7.70	18.69

Note. RT residuals are further displayed as a function of prime type (executed vs. verbally coded), classification (repetition vs. switch), and action (repetition vs. switch).

we again found a significant interaction between prime type and classification, $F(1, 38) = 22.84$, $p < .001$, $\eta_p^2 = .38$. Increases in RT residuals associated with classification switches were significantly more pronounced in executed blocks, $t(39) = 7.97$, $p < .001$, $d = 1.26$, as compared to verbally coded blocks, $t(39) = 2.31$, $p < .026$, $d = .36$. All other effects failed to reach significance, $Fs \leq 2.76$, $ps \geq .105$, $\eta_p^2 \leq .07$.

Discussion. Our findings show that, as typically observed in task-switching paradigms, task switches between trial $n − 1$ and trial n lead to significant RT increases in the probe trials relative to task repetitions. These $n − 1$ task switches, however, did not seem to impact on the effects of item-specific switches between prime and probe trial as a validation analyses correcting for the influence of $n − 1$ task switches found results equivalent to the reported analysis of probe trial RTs.

Facilitation and interference. The observed S-A and S-C effects in RTs and PEs may have been caused by either facilitatory processes in case of mapping repetitions and/or by interference when S-A and/or S-C mappings switched, impairing performance. To investigate whether both facilitation and/or interference contributed to the observed effects, we conducted paired t tests on RTs and PEs to compare performance on executed prime trials to performance on executed probe trials under conditions of action and classification repetitions and switches. As verbally coded prime trials did not provide us with any performance measure, this analysis was only conducted on executed prime and probe trials.

RT and PE results. During probe trials with full repetitions (repetitions of both action and classification mapping) RTs were significantly faster, $t(39) = 7.11$, $p < .001$, $d = 1.12$, and PEs were significantly lower, $t(39) = 6.21$, $p < .001$, $d = 0.98$, than during prime trials. When action mappings switched during probes, both RTs, $t(39) = 2.84$, $p = .007$, $d = 0.45$, and PEs, $t(39) = 3.93$, $p < .001$, $d = 0.62$, were significantly lower than during prime trials. For switches in classification mapping during

probes, RTs significantly increased in comparison to prime RTs, $t(39) = 2.97$, $p = .005$, $d = 0.47$. PEs did not significantly differ between probe trials with classification switches and prime trials, $t(39) = 0.85$, $p = .402$, $d = 0.13$. Full switches during probes (switches of both action and classification mapping) were associated with significantly increased RTs, $t(39) = 3.43$, $p = .001$, $d = 0.54$, and, in tendency, larger PEs, $t(39) = 1.91$, $p = .063$, $d = 0.30$, in comparison to prime trials.

Discussion. Our findings suggest that whereas mapping repetitions were associated with performance benefits, suggesting facilitatory effects of previously formed associations, mapping switches (at least switches in S-C mapping) were associated with performance costs, implying interference from previously formed associations. However, these results have to be interpreted with caution. As stimulus repetitions are generally associated with perceptual priming and thus recurring stimuli are typically identified faster and more accurate (e.g., Wiggs & Martin, 1998), the performed comparison of prime trial and probe trial performance is a very liberal test favoring facilitatory effects and at the same time a very conservative assessment of interference. Therefore, the absence of significant interference effects for switches in action mapping in our results should not be interpreted as a strong indication that switches in action mapping were not associated with performance costs. Rather, as we know that S-A effects are substantially smaller than S-C effects, possible interference from switches in action mapping might have been overshadowed by perceptual priming. To address the question of whether both facilitation and interference contribute to the observed effects more directly, future studies should present additional, new items during probes and compare probe performance for previously primed items to performance for these new items. By doing so, it will also be possible to assess facilitation and interference for verbally coded stimuli.

(Appendix continues)

Experiment 2

Prime RT and PE results. On executed prime trial RTs and PEs, we conducted $4 \times 2 \times 2$ mixed-design ANOVAs with the between-subjects factor prime–probe interval (one block vs. three blocks vs. seven blocks vs. one day) and the within-subjects factors classification (repetition vs. switch) and action (repetition vs. switch) to test for a priori differences between conditions.

These analyses showed nonsignificant main effects for classification, action, and prime–probe interval, RTs: $Fs \leq 1$, PEs: $Fs \leq 1.10$, $p \geq .355$, $\eta_p^2 \leq .04$. Whereas interaction between action and prime–probe interval failed to reach significance for PEs, $F(3, 76) = 1.28$, $p = .289$, $\eta_p^2 = .05$, it was significant for RTs, $F(3, 76) = 2.77$, $p = .047$, $\eta_p^2 = .10$. Subsequent paired t tests showed that this interaction was qualified by a significant difference in RTs between action switch and action repetition trials for the prime–probe interval of one block, $t(19) = 2.86$, $p = .010$, $d = 0.64$, which did not occur for the other prime–probe intervals, $t(19) \leq 1.47$, $p \geq .158$, $d \leq 0.33$. At the prime–probe interval of one block, prime trials RTs for later action repetitions were larger than for later action switches. All other interactions failed to reach significance, RTs: $Fs \leq 1.07$, $p \geq .367$, $\eta_p^2 \leq .04$, PEs: $Fs \leq 1.46$, $p \geq .231$, $\eta_p^2 \leq .06$.

Discussion. Overall, our findings support the notion that there were no a priori differences between conditions during primes. We can only attribute the significant difference between future action repetitions and switches at the prime–probe interval of one block to a chance effect. Given that the direction of the effect is opposite to the pattern we observed in executed probe trial RTs, this difference cannot account for our findings and may only have worked against the effect of action switches that we, nonetheless, observed.

Experiment 3

Prime RT and PE results. We conducted 2×2 repeated-measures ANOVAs with the within-subjects factors classification (repetition vs. switch) and action (repetition vs. switch) to test for a priori differences between conditions.

Neither the main effects of classification and action, RTs and PEs: $Fs \leq 1$, nor the interactions of classification and action showed significant effects, RTs: $F(1, 38) = 2.73$, $p = .107$, $\eta_p^2 = .07$, PEs: $F \leq 1$.

Discussion. We found neither main effects nor interactions of the factors classification and action suggesting that there were no a priori differences between conditions.