

**Multiple Priming Instances Increase the Impact of Practice-based but not Verbal
Code-based Stimulus-Response Associations**

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The data of the reported experiments as well as experiment files and syntaxes are available via the Open Science Framework: <https://osf.io/w548e/>; DOI: 10.17605/OSF.IO/W548E

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Abstract

Stimulus-response (S-R) associations, the basis of learning and behavioral automaticity, are formed by the (repeated) co-occurrence of stimuli and responses and render stimuli able to automatically trigger associated responses. The strength and behavioral impact of these S-R associations increases with the number of priming instances (i.e., practice). Here we investigated whether multiple priming instances of a special form of instruction, verbal coding, also lead to the formation of stronger S-R associations in comparison to a single instance of priming. Participants either actively classified stimuli or passively attended to verbal codes denoting responses once or four times before S-R associations were probed. We found that whereas S-R associations formed on the basis of active task execution (i.e., practice) were strengthened by multiple priming instances, S-R associations formed on the basis of verbal codes (i.e., instruction) did not benefit from additional priming instances. These findings indicate difference in the mechanisms underlying the encoding and/or retrieval of previously executed and verbally coded S-R associations.

Keywords: Stimulus-response associations; associative learning; verbal codes; automaticity; instruction

1. Introduction

“What we learn to do, we learn by doing”. This quote attributed to Thomas Jefferson exemplifies the notion that own action is necessary to learn. For a long time, psychologists have prevalently suggested that stimulus-response (S-R) associations, the basis of learning and behavioral automaticity, are formed by own action (i.e., practice). Repeated co-occurrence of stimuli and responses allows stimulus and response representations to bind together into S-R associations. These S-R associations subsequently render stimuli able to automatically trigger the retrieval of associated responses (e.g., Henson, Eckstein, Waszak, Frings, & Horner, 2014; Hommel, 1998; Logan, 1990). This automatic retrieval can even lead to erroneous responses when the currently required response does not match the response stored in the S-R association (e.g., Horner & Henson, 2011, 2012).

The formation and automatic retrieval of S-R associations can be inferred from repetition priming effects. That is, participants are faster to classify stimuli when repeatedly performing the same response rather than different responses upon them (e.g., Logan, 1990; Henson et al., 2014). Although a single priming instance is sufficient for automatic S-R associations to emerge (e.g., Horner & Henson, 2009; Hsu & Waszak, 2012; Moutsopoulou, Yang, Desantis, & Waszak, 2015; Waszak, 2010; Waszak, Hommel, & Allport, 2003), the behavioral impact of S-R associations typically increases with the number of priming instances (e.g., Logan, 1988, 1990; Horner & Henson, 2009; Moutsopoulou et al., 2015). For instance, Horner and Henson (2009) had their participants classify various everyday objects according to their size relative to a reference object. Participants either classified objects once or thrice with the same S-R mapping before the resulting S-R associations were probed. During probe trials, the size referent could either remain the same, so that participants still had to perform the same responses as during primes, or the size referent and with it the required response for a

stimulus could switch. Analyzing probe trial performance, Horner and Henson (2009) found that repetition priming effects – that is, differences in the reaction times (RTs) and/or error rates (PEs; percentages of error) between item-specific response repetitions and response switches – were more pronounced when stimuli had been primed multiple times. That is, the more often participants had practiced responses, the stronger the behavioral impact of the resulting S-R associations was.

According to instance theory (e.g., Logan, 1990), repetition priming effects emerge as S-R instances, formed by previous pairings of stimuli and responses, race against an algorithmic process that computes responses anew. When the currently required response matches the response stored in the S-R instance, reactions are faster on those trials on which instance retrieval wins the race. Thus, on average reactions are faster when S-R mappings repeat rather than switch. Instance theory explains the increased impact of prior S-R mappings with more priming instances (i.e., the increased performance differences between response repetitions and response switches) by suggesting that separate instances are created each time a stimulus and a response are paired. The more identical instances are generated, the more often instance retrieval wins the race and the larger the performance benefit of response repetitions is in comparison to response switches.

A pattern of results similar to that observed by Horner and Henson (2009) emerged when both the classification task participants were to perform upon stimuli and participants' action could independently repeat or switch between the prime instance(s) of a stimulus and its probe instances (Moutsopoulou et al., 2015; see also Figure 1). Participants were to classify everyday objects either according to their size in relation to a reference box or according to whether they were mechanic or not by pressing a left or right key. Moutsopoulou et al. (2015) used task cues (e.g., "S + L" for "small vs. large") to indicate both the classification task participants should perform on a subsequent stimulus as well as the classification-action mapping of a trial. Stimuli were primed with

the same classification-action mapping either once or four times before they were probed (see Figure 2, upper panel). Both switches in action mapping and switches in classification mapping (i.e., switches between classification tasks) between the prime instance(s) and probe instance of a specific stimulus led to longer RTs and increased error rates in comparison to repetitions of the respective mappings. Importantly, however, performance differences between repetitions and switches were more pronounced when stimuli had been primed multiple times. As the behavioral effects of switches in stimulus-action mapping and stimulus-classification mapping did not interact, Moutsopoulou et al. (2015) concluded that S-R associations consist of two distinct components, Stimulus-Action (S-A) and Stimulus-Classification (S-C) associations, that can each be strengthened by multiple priming instances (see also Koch & Allport, 2006, for evidence of stimulus-task or S-C associations in task switching).¹

This interpretation is in line with the idea of an associative mechanism (see also Horner & Henson, 2009). Rather than creating several identical S-R instances, having participants repeatedly respond to stimuli with the same S-R mapping may also strengthen the initially formed S-R association and thus yield a stronger influence on performance. Regardless of whether practice benefits are explained by a race of an automatic instance retrieval against an algorithmic processing route or by an associative mechanism, theories agreed that S-R associations are formed by active task execution (i.e., practice).

¹ Prior research on S-R associations (e.g., Allenmark, Moutsopoulou, & Waszak, 2015; Horner & Henson, 2009, 2011; Moutsopoulou et al., 2015) has consistently regarded S-A and S-C associations (or their equivalents) as sub-components of a generic concept of S-R associations. This terminology was originally introduced, as many preceding (and also later) studies that used the term S-R associations did not differentiate S-A and S-C associations and it is therefore in some cases not possible to infer, whether S-A and/or S-C associations were assessed in these studies. We will therefore speak of S-A and S-C associations when referring to our work and speak of S-R associations when discussing other studies that did not differentiate between the S-A and S-C component.

Yet, in recent years the notion that S-R associations, and with them behavioral automaticity, can only be achieved through own action has been questioned. Various authors suggested that not only own action, but also mere instruction may bind stimuli and responses together (e.g., Brass, Wenke, Spengler, & Waszak, 2009; Cohen-Kadosh & Meiran, 2007, 2009; Meiran, Kessler, Cole, & Braver, 2015; Liefoghe, Wenke, & De Houwer, 2012; Waszak, Wenke, & Brass, 2008; Wenke, De Houwer, De Winne, & Liefoghe, 2015; Wenke & Frensch, 2005; Wenke, Gaschler, & Nattkemper, 2007; Waszak, Pfister, & Kiesel, 2013). For instance, Liefoghe, Wenke, and De Houwer (2012) demonstrated an instruction-based task-rule congruency effect. In each block, participants first received instructions regarding the responses (left vs. right key presses) they had to perform upon bivalent stimuli (upright or italicized letters). Subsequently, participants first had to judge the orientation of the stimuli (diagnostic task), before the stimuli changed colour and participants had to judge letter identity (inducer task). Although they had never applied the S-R mappings instructed for the letter identity task before, when participants performed the preceding diagnostic task, RTs were shorter when stimuli required the same rather than different responses in the two tasks. This finding indicates that the merely instructed S-R mapping for the inducer task affected performance on the diagnostic task.

However, instruction-based effects seem to be restricted by several pre-conditions (Meiran, Cole, & Braver, 2012). First, participants need to have the intention to apply the respective instructions (Wenke, Gaschler, Nattkemper, & Frensch, 2009). Furthermore, storage resources in the region of direct access (see Oberauer, 2002, 2010), a working memory equivalent, have to be available (Cohen-Kadosh & Meiran, 2007; Meiran & Cohen-Kadosh, 2012). Thus, the reported instruction-based effects do not imply that automatic S-R associations can be built by mere instruction, but instead instruction only allows for conditionally automatic S-R links in the sense of a prepared reflex (e.g.;

Hommel, 2000; Woodworth, 1938). That is, during instruction, participants have to actively configure their cognitive system to respond to a stimulus with a certain action. This intentional process then allows for automatic S-R translation when the stimulus appears. The implementation of an intentional set during instruction, however, is not automatic and conversely instructions only lead to automatic S-R retrieval when participants have the intention to apply them.

Nevertheless, a recent study using an alternative form of instruction, verbal coding, has been able to provide evidence for instruction-based automatic S-C and S-A retrieval independent of an intention to apply instructions (Pfeuffer, Moutsopoulou, Pfister, Waszak, & Kiesel, 2017). Pfeuffer, Moutsopoulou et al. (2017) used an item-specific priming paradigm adapted from Moutsopoulou et al. (2015) in which everyday objects appeared once as a prime and, several trials later, once as a probe. There were two types of blocks: Blocks with response execution during both prime and probe trials like in the study by Moutsopoulou et al. (2015; short: executed blocks) and blocks with verbally coded prime trials and response execution in probe trials only (see Figure 2, lower panel). In the prime and probe trials of executed blocks, participants actively classified objects according to their size or according to whether they contained a mechanism or not by pressing a left or right key in accordance with a preceding task cue (e.g., „K + G“ for „klein vs. groß“; Eng. „small vs. large“). In the prime trials of verbally coded blocks (i.e., instruction blocks), participants passively viewed objects and simultaneously heard verbal codes denoting class and action without acting themselves. For instance, participants passively attended to the image of an apple and heard „klein, rechts“ (Eng: „small, right“) via the headphones. During the corresponding probe trials of stimuli primed by verbal coding, participant actively classified objects by pressing a left or right key. Thus, probe trials were equivalent for executed and verbally coded blocks. Between the prime and probe instance of a specific stimulus, the S-C and S-A mappings associated

with it either repeated or switched. Like Moutsopoulou et al. (2015), Pfeuffer, Moutsopoulou et al. (2017) differentiated between a S-A association between a stimulus and the motor response performed on it and a S-C association between a stimulus and its task-specific classification (e.g., as large versus small; see also Horner & Henson, 2009; Moutsopoulou & Waszak, 2012; Moutsopoulou et al., 2015, for further information on S-A and S-C associations). Consequently, between the prime and probe instance of a stimulus both its S-A mapping (i.e., the action, left versus right response, to be performed on it) and its S-C mapping (i.e., the classification task, size versus mechanism, to be performed on it) could independently repeat or switch.

Both when participants had actively classified stimuli during executed prime trials and when they had passively attended to verbal codes during verbally coded prime trials, switches in S-A or S-C mapping between the prime and probe instance of a stimulus were associated with longer RTs and increased PEs in the probes in comparison to repetitions of the respective mappings. Pfeuffer, Moutsopoulou et al. (2017) therefore concluded that both S-A and S-C associations could be established by task execution as well as verbal coding (i.e., a special form of instruction).

Crucially, participants were not instructed to apply verbal codes during probes and an application of verbal codes was not advantageous to performance as repetitions and switches in S-A and S-C mapping between the prime and probe instance of a stimulus occurred equally frequently. Thus, it is unlikely that the observed influence of verbally coded S-C and S-A mappings on probe performance resulted from participants' intention to apply verbal codes. Furthermore, a second experiment indicated that the retrieval of verbal code-based S-C and S-A associations did not depend on working memory capacity. Thus, the authors concluded that the observed effects of verbal coding suggest automatic S-C and S-A associations, formed on the basis of verbal codes (i.e., instruction), that do not depend on intention or working memory capacity.

Although verbal codes differ from the S-R instructions used in prior studies (e.g., Cohen-Kadosh & Meiran, 2007, 2009; Liefooghe et al., 2012) in that they are not formulated in an if-then format and do not have to be applied later on, these findings suggest that under certain conditions, automatic S-C as well as S-A associations can be formed on the basis of instruction. That is, at least when using a specific form of instruction, verbal codes, S-C and S-A associations that affect later behavior independent from an intention to apply instructed mappings can be formed in the absence of own action. Interestingly, Pfeuffer, Moutsopoulou et al. (2017) found that these verbal code-based S-C and S-A associations were also similarly temporally stable and resilient against overwriting as S-C and S-A associations formed on the basis of task execution.

Here, we addressed the question whether these verbal code-based S-C and S-A associations benefit from multiple priming instances² as do S-C and S-A associations established on the basis of active task execution (i.e., practice). That is, we hypothesized that when participants had actively classified stimuli by responding with the same S-C and S-A mappings multiple times rather than only once, repetition priming effects (i.e., performance differences between S-C and S-A mapping repetitions and switches during probe trials) for both repeated S-C and S-A mappings should be increased. In line with previous studies (e.g., Horner & Henson, 2009; Moutsopoulou et al., 2015), this pattern of results would indicate that participants not only formed both S-C and S-A associations during task execution, but that these S-C and S-A associations were also strengthened (or that more instances of these S-C and S-A associations were generated) when they were primed multiple times. Based on this benefit of multiple priming instances for execution-based S-C and S-A associations, we aimed to explore whether verbal code-based S-C and S-A associations could also benefit from multiple priming instances. That is, we

² Please note that we use the term instances to refer to the trials in which a specific stimulus occurs. The term is not meant to presuppose any theory.

investigated whether multiple instances of verbal coding with the same S-C and S-A mappings also led to more pronounced repetition priming effects in comparison to a single verbal code priming instance. If S-C and S-A associations created on the basis of verbal codes were strengthened with repeated presentation like executed S-C and S-A associations, this would support the idea that execution-based and verbal code-based S-C and S-A associations rely on similar processes and memory structures. Furthermore, it would imply that S-C and S-A associations can be strengthened without own action, suggesting that verbal codes could possibly substitute active practice when training stimulus-based responses.

In order to investigate the influence of the number of priming instances on execution-based and verbal code-based S-C and S-A associations we adapted the paradigm of Pfeuffer, Moutsopoulou et al. (2017). Stimuli were either primed by active task execution or verbal coding and S-C and S-A associations were tested during probe trials in which participants actively classified stimuli. Crucially, in half of the blocks of each block type (executed vs. verbally coded) stimuli were primed only once and in the other half, stimuli were primed four times with the same S-C and S-A mappings before they were probed.

To foreshadow our results, we find that whereas execution-based S-C and S-A associations benefit from multiple priming instances, verbal code-based S-C and S-A associations do not.

2. Methods

2.1 Participants

Thirty-nine participants (9 male, 5 left handed, mean age = 23.1 years) took part and provided written informed consent prior to their participation. Sample size was determined based on the effect size reported in a previous study investigating S-C and S-A associations based on task execution and verbal codes in an item-specific priming paradigm (Pfeuffer, Moutsopoulou et al., 2017). G*Power (Faul, Erdfelder, Lang, &

Buchner, 2007) suggested a sample size of 32 to detect effects of $\eta_p^2 = 0.05$ with 90% power at an alpha level of 5%. As the study was run in two sessions per participant, we sampled 40 participants expecting an attrition rate of up to 20%. The data of one additional participant had to be excluded as that participant was accidentally shown the same object images during the first and second session of the experiment.

2.2 Stimuli and apparatus

Participants sat approximately 60 cm from a 24" LCD screen (1920 pixels x 1080 pixels) in a dimly lit, sound attenuated room. They wore headphones throughout the experiment and their index fingers rested on two external keys placed in front of them to the left and right (key distance 13.5 cm).

Images depicting everyday objects adapted from a prior study (Pfeuffer, Moutsopoulou et al., 2017; adapted from a set by Brady, Konkle, Alvarez, and Oliva, 2008, and Moutsopoulou et al., 2015; image size 256 pixels x 256 pixels) were used as target stimuli. Each of the 512 objects could easily be classified according to its real-life size relative to a reference box (box dimensions: 37.5 cm x 30 cm x 13.5 cm) and according to whether it contained a mechanism or not. The final target stimulus set consisted of 128 object images for each of the possible combinations of size and mechanism categories (small - mechanic, small - non-mechanic, large - mechanic, large - non-mechanic). Twenty-four additional object images were used in a preceding practice.

Target stimuli were preceded by task-specific cues that indicated not only the to-be-performed task, but also the key-classification assignment. The task cues for the size task were "K + G" and "G + K". The letters corresponded 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 "mechanic" ("mechanisch"), and "non-mechanic" ("nicht-mechanisch"). Participants classified target stimuli by pressing the

key spatially corresponding to the correct task-specific classification. For instance, if the task cue “M + N” preceded the image of a car, participants were to press the left key to indicate that the car was mechanic (see Figure 2).

Furthermore, voice recording playbacks (1.8 – 2.3 s, about 65 dB) were used as verbal codes informing participants about the class and action associated with a target stimulus in verbally coded prime trials (e.g., “klein, rechts”, Eng. “small, right”). All verbal code recordings featured an emotionally neutral, female voice.

2.3 Design and procedure

Before starting with the task proper, participants performed 8 practice blocks (4 executed, 4 verbally coded), half of them with one prime instance and half of them with four prime instances per stimulus. The subsequent main experiment was run in two sessions of 64 blocks (32 executed, 32 verbally coded; half primed once, half primed four times), resulting in a total of 1280 prime trials, 512 probe trials and 32 probe trials per condition. Within each session, executed and verbally coded blocks appeared equally often in random sequence. Furthermore, in half of the executed and verbally coded blocks stimuli were primed once (4 prime trials, 4 probe trials) and in the other half stimuli were primed four times (16 prime trials, 4 probe trials). Participants were informed about the prime type of the ensuing block prior to its beginning. Specifically, they were told whether they would have to respond to the stimuli from the beginning of the block (executed blocks) or first attend to the verbal codes and only respond to the stimuli later (verbally coded blocks). Participants were not informed whether stimuli would be primed once or four times each. That is, in verbally coded blocks, the appearance of a task cue instead of a verbal code in the probe trials indicated that participants now had to respond to stimuli.

Each block consisted of a prime phase and a probe phase. Per block, four new stimuli were randomly chosen from the stimulus set. During the prime phase, these four stimuli

were primed once or four times and subsequently reappeared once during the probe phase, two to seven trials after they were last primed (see Figure 2). When stimuli were primed multiple times, all four stimuli of a block were presented before any of the stimuli reappeared and the lag between the prime instances of a specific stimulus was two to seven trials. Thus, stimuli that were primed once appeared twice throughout the entire experiment, once as a prime and once as a probe, whereas stimuli that were probed four times appeared five times in total, four times as a prime and once as a probe. Crucially, each stimulus only occurred in a single block and did not recur during the experiment.

In executed blocks, participants actively classified stimuli by pressing a key during both prime and probe trials. Each trial started with the presentation of the task cue (700 ms), followed by the target stimulus (until response, maximum duration 2000 ms). Participants responses were followed by a feedback screen (500 ms) informing the participant about the accuracy of their classification response (“Richtig!”, Eng.: “correct!” vs. “Fehler!”, Eng.: “error!”). In case participants did not respond within the time limit of 2000 ms, the feedback message “zu langsam!” (Eng.: “too slow!”) was displayed. This structure was the same for executed prime and probe trials.

The structure of verbally coded probe trials was equivalent to executed probe trials. In verbally coded prime trials, however, participants did not actively classify objects. They passively attended to target stimuli and simultaneously were presented with verbal codes denoting class and action via the headphones. Target stimuli were presented for an initial 700 ms before the verbal codes were played back while target stimuli remained on screen for additional 3000 ms. Participants were instructed not to perform any actions during verbally coded prime trials, but to attend to the presented verbal codes. Additionally, they were instructed to always position their fingers on the keys at the beginning of a block irrespective of its type to be ready to respond as fast as possible when required. We assessed participants RTs and PEs depending on the prime type

(executed vs. verbally coded), the number of prime trials (1 vs. 4), classification (repetition vs. switch), and action (repetition vs. switch).

When items were primed multiple times S-A and S-C mappings were consistent across all four prime instances of a stimulus. However, between the item-specific prime instance(s) of a stimulus and its probe instance, the action and classification mappings repeated or switched independently resulting in four possible switch conditions (full repetition, action switch, classification switch, full switch; see Figure 1). Each switch condition was equally frequent in each of the two experimental sessions and for each combination of prime type (executed vs. verbally coded) and number of prime instances (1 vs. 4), so that participants could not predict the probe S-A and/or S-C mappings of specific stimuli.

3. Results

3.1 Prime trial analyses

As verbally coded prime trials did not provide any performance measures, only executed prime trials were analyzed. Prime trials with response omissions (0.3%) were excluded from all analyses. Furthermore, in the condition with four prime instances only stimuli participants had correctly classified during their preceding prime instances were considered (9.3% excluded). Finally, for RT analyses, trials with erroneous responses (5.8%) as well as RT outliers (1.3%) were excluded. Outliers were defined as RTs deviating by more than 3 standard deviations in either direction from their respective individual cell means.

To check whether conditions differed a priori (i.e., during prime instances), we conducted 2 x 2 x 2 repeated measures analysis of variance (ANOVA) with the within-subjects factors number of prime instances (1 vs. 4), classification (repetition vs. switch), and action (repetition vs. switch) on RTs and error rates (PE, percentage of errors) of the first prime instance of each condition. Neither the analysis of prime RTs, $F(1,38) \leq 1.81$,

$p \geq .186$, $\eta_p^2 \leq .05$, nor the analysis of prime PEs, $F(1,38) \leq 2.99$, $p \geq .092$, $\eta_p^2 \leq .07$, revealed significant differences between conditions.

Moreover, we used a one-way ANOVA to investigate RTs and PEs across the four prime instances of a stimulus in the executed blocks. Both RTs, $F(3,114) = 176.06$, $p < .001$, $\eta_p^2 = .82$, and PEs, $F(3,114) = 53.29$, $p < .001$, $\eta_p^2 = .58$, significantly differed across prime instances. The more often participants had already responded to a stimulus the faster and more accurately they classified it. Subsequent paired t -tests showed that both RTs and PEs continuously decreased from prime instance 1 to 2, RTs: $t(38) = 9.56$, $p < .001$, $d = 1.53$; PEs: $t(38) = 7.17$, $p < .001$, $d = 1.15$, from prime instance 2 to 3, RTs: $t(38) = 9.12$, $p < .001$, $d = 1.46$; PEs: $t(38) = 1.91$, $p = .064$, $d = 0.31$, and from prime instance 3 to 4, RTs: $t(38) = 6.36$, $p < .001$, $d = 1.02$; PEs: $t(38) = 3.73$, $p = .001$, $d = 0.60$.

3.2 Probe trial analyses

For probe analyses the first probe trial of each block was excluded, as the switch from passive listening to active responding in verbally coded blocks could have influenced participants' performance. Furthermore, probe trials with response omissions (0.3%) or probe trials with incorrect responses (5.8%) or response omissions (0.3%) during the corresponding prime trials were excluded from all analyses. Additionally, if participants had accidentally responded to a verbally coded prime (1.9%), the corresponding probe trial was excluded from all analyses.³ For RT analysis, trials with erroneous responses (8.0%; average exclusion rate for RT analysis due to all criteria 15.1%) as well as RT outliers (1.0%) were additionally excluded.

³ Note that only probe trials of stimuli to which participants had correctly responded during their prime trial(s) were included in probe analyses. Thus, probe analyses overall contained less observations per cell for executed S-C and S-A mappings in comparison to verbally coded S-C and S-A mappings.

3.2.1 Probe RT analyses

A 2 x 2 x 2 x 2 repeated measures ANOVA with the within-subjects factors prime type (executed vs. verbally coded), number of prime instances (1 vs. 4), classification (repetition vs. switch), and action (repetition vs. switch) was conducted on probe trial RTs. Significant two-way interactions were further explored by using paired t-tests and significant three-way interactions were examined by conducting two 2 x 2 repeated measures ANOVAs.

This analysis revealed a significant main effect of prime type, $F(1,38) = 34.26$, $p < .001$, $\eta_p^2 = .47$, with participants responding significantly faster on verbally coded probe trials than on executed probe trials (see Figure 3; see Table 1 for an overview of the ANOVA results). Furthermore, the main effects of classification, $F(1,38) = 143.24$, $p < .001$, $\eta_p^2 = .79$, and action, $F(1,38) = 31.19$, $p < .001$, $\eta_p^2 = .45$, were significant. Switches in classification and action mapping between the prime and probe instances of a stimulus were associated with significantly increased RTs in comparison to repetitions of the respective mappings.

Furthermore, number of prime instances significantly interacted with classification, $F(1,38) = 23.78$, $p < .001$, $\eta_p^2 = .39$. This interaction was further explained by a three-way interaction of prime type, number of prime instances, and classification, $F(1,38) = 10.63$, $p = .002$, $\eta_p^2 = .22$. The number of prime instances and classification significantly interacted in executed blocks, $F(1,38) = 26.86$, $p < .001$, $\eta_p^2 = .41$, with classification effects being more pronounced with more prime instances, but did not interact in verbally coded blocks, $F < 1$.

Moreover, the three-way interaction of prime type, the number of prime instances, and action reached significance, $F(1,38) = 4.92$, $p = .033$, $\eta_p^2 = .12$, with the number of prime instances and action significantly interacting in executed blocks, $F(1,38) = 6.77$, p

= .013, $\eta_p^2 = .15$, with action effects being more pronounced for multiple prime instances rather than one, but not in verbally coded blocks, $F < 1$.

Furthermore, prime type interacted with number of prime instances, $F(1,38) = 9.25$, $p = .004$, $\eta_p^2 = .20$. In verbally coded blocks, RTs were significantly reduced when stimuli were primed four times instead of only once, $t(38) = 3.67$, $p = .001$, $d = 0.59$. In executed blocks, RTs did not differ between stimuli primed once and stimuli primed four times, $t(38) = -0.43$, $p = .672$, $d = -0.07$.

Both classification and action significantly interacted with prime type, Classification X Prime Type: $F(1,38) = 66.83$, $p < .001$, $\eta_p^2 = .64$; Action X Prime Type: $F(1,38) = 24.31$, $p < .001$, $\eta_p^2 = .39$. Classification switches were associated with significant RT increases in comparison to classification repetitions in both executed blocks, $t(38) = 11.75$, $p < .001$, $d = 1.88$, and verbally coded blocks, $t(38) = 4.29$, $p < .001$, $d = 0.69$, but RT increases were more pronounced in executed blocks. Action switches were associated with significantly prolonged RTs in comparison to action repetitions in executed blocks, $t(38) = 7.53$, $p < .001$, $d = 1.21$, but RTs for action switches and action repetitions did not differ in verbally coded blocks, $t(38) = -0.59$, $p = .558$, $d = -0.09$.

Additionally, classification and action interacted, $F(1,38) = 9.34$, $p = .004$, $\eta_p^2 = .20$. This interaction was further qualified by a three-way interaction of prime type, classification, and action, $F(1,38) = 4.68$, $p = .037$, $\eta_p^2 = .11$. Classification and Action significantly interacted in executed blocks, $F(1,38) = 10.23$, $p = .003$, $\eta_p^2 = .21$, with RT differences between action switch and action repetition being more pronounced when classification repeated, but not in verbally coded blocks, $F < 1$. The main effect of the number of prime instances, $F(1,38) = 1.69$, $p = .202$, $\eta_p^2 = .04$, and all other interactions, $F(1,38) \leq 2.35$, $p \geq .134$, $\eta_p^2 \leq .06$, failed to reach significance.

To draw further inferences about the null-effects we observed in verbally coded blocks for the critical interactions of the number of prime instances and classification as well as the number of prime instances and action, we additionally conducted a Bayesian Repeated Measures ANOVA with default prior scales using JASP (version 0.8.0.0, Love et al., 2015; see Rouder, Morey, Verhagen, Swagman, & Wagenmakers, in press; Rouder, Speckman, Sun, Morey, & Iverson, 2009, for information on Bayesian statistics). This analysis allowed us to assess the evidence in favor of the null hypothesis that in verbally coded blocks S-C and S-A effects did not differ depending on the number of times the respective S-C and S-A mappings had been primed. For the analyses, we compared the null hypotheses that S-C/S-A effects did not differ depending on the number of priming instances to the alternative hypotheses that S-C/S-A effects significantly differed with the number of priming instances. The Bayes-factor (BF_{01}) indexes how strongly the data is in favor of the null hypothesis. Our results indicated that for the interaction of the number of prime instances and classification the null hypothesis was 5.04 times more likely given the data than the alternative hypothesis ($BF_{01} = 5.04$). For the interaction of the number of prime instances and action, the null hypothesis was 5.94 times more likely than the alternative hypothesis given the data ($BF_{01} = 5.94$). These Bayes factors are considered as moderate evidence in favor of the null hypothesis (see Jarosz & Wiley, 2014).

Finally, to further rule out that overall slower RTs in executed as compared to verbally coded blocks affected the results, we conducted additional paired *t*-tests comparing RTs on probe trials with full repetitions (item-specific repetitions of both classification and action mapping) in executed and verbally coded blocks. These *t*-tests showed that full repetition probe RTs did not significantly differ between stimuli primed once by active task execution and stimuli primed once by verbal coding, $t(38) = 1.51$, $p = .139$, $d = 0.24$. Furthermore, full repetition probe RTs also did not significantly differ

between stimuli primed once by active task execution and stimuli primed four times by verbal coding, $t(38) = -0.68$, $p = .501$, $d = 0.11$. These findings suggest that the overall increased RTs for executed probe trials in comparison to verbally coded probe trials did not result from a general RT difference between conditions, but from increased interference (i.e., RT costs) for switches in S-A and S-C mapping in executed probe trials as compared to verbally coded probe trials (see e.g. Horner & Henson, 2011, for evidence that both facilitation and interference contribute to the item-specific priming effects observed for S-C and S-A associations).

3.2.2 Probe PE analyses

An equivalent $2 \times 2 \times 2 \times 2$ repeated measures ANOVA was conducted on probe PEs. Participants committed fewer errors in verbally coded probe trials than in executed probe trials, $F(1,38) = 38.74$, $p < .001$, $\eta_p^2 = .51$. Furthermore, both the main effects of classification, $F(1,38) = 100.02$, $p < .001$, $\eta_p^2 = .73$, and action, $F(1,38) = 27.34$, $p < .001$, $\eta_p^2 = .42$, were significant with mapping switches being associated with more errors than mapping repetitions.

The number of prime instances interacted with classification, $F(1,38) = 5.91$, $p = .020$, $\eta_p^2 = .14$. Importantly, this interaction was further explained by a three-way interaction of prime type, the number of prime instances, and classification, $F(1,38) = 5.37$, $p = .026$, $\eta_p^2 = .12$. The number of prime instances and classification significantly interacted in executed blocks, $F(1,38) = 7.27$, $p = .010$, $\eta_p^2 = .16$, but not in verbally coded blocks, $F < 1$. In executed blocks, the PE difference between item-specific switches and repetitions in S-C mapping between prime and probe was more pronounced when stimuli were primed four times.

Moreover, the number of prime instances and action interacted, $F(1,38) = 4.95$, $p = .032$, $\eta_p^2 = .12$. Error rate differences between S-A switches and repetitions were more

pronounced when stimuli were primed four times, $t(38) = 4.98, p < .001, d = 0.80$, in comparison to a single time, $t(38) = 2.63, p = .012, d = 0.42$. The three-way interaction of prime type, the number of prime instances, and action failed to reach significance, $F(1,38) = 1.13, p = .294, \eta_p^2 = .03$.

Furthermore, the interaction of prime type and the number of prime instances reached significance, $F(1,38) = 20.09, p < .001, \eta_p^2 = .35$. In executed blocks, four priming instances were associated with a significantly increased PE in comparison to one priming instance, $t(38) = -3.59, p = .001, d = -0.57$. In verbally coded blocks, four priming instances were associated with a significantly reduced PE in comparison to a single priming instance, $t(38) = 2.93, p = .006, d = 0.47$.

Finally, both classification, $F(1,38) = 34.00, p < .001, \eta_p^2 = .47$, and action, $F(1,38) = 10.67, p = .002, \eta_p^2 = .22$, significantly interacted with prime type. Switches in S-C mapping between the prime and probe instances of a stimulus were associated with increased error rates as compared to repetitions both in executed blocks, $t(38) = 9.60, p < .001, d = 1.54$, and in verbally coded blocks, $t(38) = 3.21, p = .003, d = 0.51$. Error rate differences between classification switches and repetitions were, however, more pronounced in executed blocks. In contrast, item-specific switches in S-A mapping were only associated with more errors than repetitions in executed blocks, $t(38) = 4.96, p < .001, d = 0.79$, although a non-significant trend was visible in verbally coded blocks, $t(38) = 1.76, p = .087, d = 0.28$. The main effect of the number of prime instances, $F(1,38) = 2.95, p = .094, \eta_p^2 = .07$, and all other interactions failed to reach significance, $F(1,38) \leq 1.26, p \geq .270, \eta_p^2 \leq .03$.

The error rate data of verbally coded blocks were additionally subjected to a Bayesian Repeated Measures ANOVA equivalent to the one conducted on RTs. This analysis revealed moderate evidence in favor of the null hypothesis for both the interaction of the

number of prime instances and classification ($BF_{01} = 5.73$) and the interaction of the number of prime instances and action ($BF_{01} = 4.35$) in verbally coded blocks.

4. Discussion

We used an item-specific priming paradigm adapted from Pfeuffer, Moutsopoulou et al. (2017) to investigate whether the number of priming instances influences the behavioral effects of S-C and S-A associations formed by active task execution and passively attending to verbal codes. During prime instances, participants either actively classified stimuli according to size or mechanism by pressing a key (executed blocks) or passively attended to verbal codes denoting class and action while viewing stimuli (verbally coded blocks). Stimuli were either primed once or four times with the same S-A and S-C mappings before they recurred as probes and participants had to actively classify them in both types of blocks. Between the prime instance(s) and the probe instance of a stimulus, S-C and S-A mappings independently repeated or switched, allowing us to assess the strength of the resulting S-C and S-A associations by examining performance differences between switches and repetitions in the respective S-C and S-A mappings.

First, we replicated the findings of Pfeuffer, Moutsopoulou et al. (2017) that both active task execution and passively attending to verbal codes leads to the creation of S-C associations. Both when participants had actively classified stimuli during primes (executed blocks) and when they had merely attended to verbal codes, switches in S-C mapping between the prime and probe instances of a stimulus were associated with RT and PE increases relative to S-C mapping repetitions. Although, the RT and PE increases associated with S-C switches were more pronounced in executed blocks, significant differences between switches and repetitions in S-C mapping were present in both executed and verbally coded blocks. These findings indicate that S-C associations were

formed both based on task execution (i.e., practice) and based on verbal codes (i.e., instruction).⁴

Furthermore, as in prior studies (e.g., Moutsopoulou et al., 2015; Pfeuffer, Moutsopoulou et al., 2017) in executed blocks, switches in S-A mapping were associated with prolonged RTs and increased PEs in comparison to S-A repetitions, suggesting that automatic S-A associations had been formed during primes. However, in contrast to Pfeuffer, Moutsopoulou et al. (2017), we found significant performance differences between repetitions and switches in action mapping only in executed blocks and not in verbally coded blocks. This result is in line with findings suggesting that S-A associations, especially verbal code-based S-A associations, generally have less pronounced behavioral impact than S-C associations and are therefore less reliably found (e.g., Hsu & Waszak, 2012; Moutsopoulou et al., 2015; Pfeuffer, Moutsopoulou et al., 2017; Pfeuffer, Hosp, Kimmig, Moutsopoulou, Waszak, & Kiesel, 2017). Nevertheless, the absence of significant performance differences between S-A switches and S-A repetitions in verbally coded blocks, not only points towards the fragile nature of verbal code-based S-A associations. Importantly, it also implies that we have to interpret our findings regarding the influence of the number of prime instances on the strength of S-A associations formed on the basis of task execution and verbal codes with caution. As in the absence of significant S-A effects in verbally coded blocks, a modulation of the strength of verbal code-based S-A associations by the number of prime instances cannot reliably be observed.

Moreover, we found that action and classification significantly interacted in executed blocks, indicating that, instead of independent S-A and S-C associations, hierarchical

⁴ Please note that the processes by which instructions and verbal codes specifically lead to the formation of S-C and S-A associations remain to be investigated. Possibly, these processes are similar to the processes underlying the formation of S-C and S-A associations, for instance, on the basis of observation.

task representations (i.e., S-C-A associations), that allow for the context-specific retrieval of responses, might have been formed. That is, the interaction of classification and action suggests that participants might have associated stimuli with classifications (S-C) and these classifications with actions (C-A). In contrast to this finding, previous studies observed independent effects of switches in S-C and S-A mapping, suggesting that two independent associations between stimuli and classifications and stimuli and actions had been formed (e.g., Moutsopoulou et al., 2015; Pfeuffer, Moutsopoulou et al., 2017; Pfeuffer, Hosp et al., 2017).⁵

Interestingly, both the study of Moutsopoulou et al. (2015) and our present study involved multiple priming instances. We therefore cannot attribute the different finding to the number of priming instances. Future studies will have to determine whether other factors influenced the encoding and/or retrieval of S-C and S-A mappings leading to hierarchical task representations instead of independent S-C and S-A associations as observed in prior studies (e.g., Moutsopoulou et al., 2015; Pfeuffer, Moutsopoulou et al., 2017; Pfeuffer, Hosp et al., 2017). At present, we cannot discern a difference between these studies that could be responsible for this contradicting pattern of results. Future

⁵ Note that the pattern of results resembles response repetition effects observed in task switching studies (e.g., Druey & Hübner, 2008 a, b; Hübner & Druey, 2006, 2008; Koch, Schuch, Vu, & Proctor, 2011; Rogers & Monsell, 1995; Schuch & Koch, 2004; Steinhauser, Hübner, & Druey, 2009; see also Kiesel, Steinhauser, Wendt, Falkenstein, Jost, Philipp, & Koch, 2010, for a review on task switching addressing this aspect). Participants respond faster for response repetitions than response switches when the task repeats from trial N-1 to trial N. Yet, for task switches there is no or even a reversed effect and participants tend to respond slower for response repetitions than response switches. One possible explanation for this finding in task switching (association account, e.g., Rogers & Monsell, 1995) suggests that category-response associations are strengthened by task execution, leading to benefits of response repetitions when the task repeats and costs of response repetitions when the task switches. Similarly, in this item-specific priming paradigm, an interaction of classification and action would suggest that there are not only item-specific associations between stimuli and classifications (S-C) and stimuli and actions (S-A), but also associations between classifications and actions (C-A).

studies will need to show whether the interaction between classification and action replicates.

Furthermore, as expected, we found that both S-C and S-A associations formed on the basis of active task execution were modulated by the number of prime instances. In executed blocks, RT and PE increases associated with switches in S-C and S-A mappings were generally larger when stimuli were primed four times instead of only once. This finding replicates previous studies on execution-based S-C and S-A associations (Horner & Henson, 2009; Moutsopoulou et al., 2015) and supports the notion that S-C and S-A associations formed by active task execution are strengthened by multiple priming instances or, alternatively, that multiple instances are generated. Note, however, that we cannot distinguish between the two accounts. Further studies will be necessary to elaborate on the theoretically interesting distinction between a strengthening of a single association and the formation of additional instances.

Importantly, however, the influence of the number of prime instances on the strength of S-C and S-A associations differed between S-C and S-A associations formed on the basis of active task execution and on S-C and S-A associations formed on the basis of verbal codes. Whereas the strength of execution-based S-C and S-A associations (i.e., the impact of previous S-C and S-A mappings on performance) increased with the number of priming instances, this was not the case for verbal code-based S-C (and S-A) associations. We found no indication that the priming effects associated with verbal code-based S-C (and S-A) associations were influenced by the number of verbal code-based prime instances. Furthermore, Bayesian statistics provided moderate evidence that priming effects did not differ between stimuli that had been primed by verbal coding once and four times.

Due to the absence of an S-A effect in verbally coded blocks, these findings cannot be taken as strong evidence supporting the idea that the strength of execution-based but

not verbal code-based S-A associations increases with the number of prime instances. However, for S-C associations, the finding that the behavioral impact of S-C associations is modulated by the number of prime instances in executed blocks, but not in verbally coded blocks, suggests that only S-C associations established by task execution benefit from multiple priming instances.

Recent findings showed that automatic S-C and S-A associations (i.e., associations retrieved independent from current intentions and working memory capacity) that are temporally stable and resilient against overwriting cannot only be established by active task execution (i.e., own action) but also by passively attending to verbal codes (Pfeuffer, Moutsopoulou et al., 2017). Based on their results Pfeuffer, Moutsopoulou et al. (2017) stressed the notion that S-C and S-A associations established based on active task execution and based on verbal codes might be equivalent in terms of their underlying mechanisms and processes and only differ in terms of the strength of their behavioral impact. That is, Pfeuffer, Moutsopoulou et al. (2017) suggest that differences between verbal code-based and execution-based S-R associations are only quantitative in nature.

The present findings, however, question this idea. Not only is the behavioral impact of verbal code-based S-C and S-A associations smaller than that of S-C and S-A associations formed on the basis of own action (see also Pfeuffer, Moutsopoulou et al., 2017), but in contrast to S-C and S-A associations formed by task execution, at least verbal code-based S-C associations do not benefit from multiple priming instances. It is possible that for verbal code-based S-C and S-A associations to be strengthened by repeated priming, a much larger number of priming instances is necessary than for execution-based S-C and S-A associations and we therefore failed to observe an effect with only four priming instances. If that were the case, our findings would still only illustrate a quantitative difference between S-C and S-A associations formed by task execution and verbal codes. However, the present findings might also indicate that,

although verbal code-based S-C and S-A associations equal execution-based S-R association to a certain degree (as evident from similarities in terms of temporal stability and resilience), the processes underlying their behavioral effects are not exactly the same, implying a qualitative difference. Accordingly, although instructions (verbal codes) enable us to form S-C and S-A associations without having to actively execute responses, when learning via instruction we may effectively forego the opportunity of increasing the strength of S-C (and S-A) associations through repetition.

However, assuming that verbal code-based S-C and S-A associations can truly not be strengthened by repetition, this does not necessarily only constitute a disadvantage for verbal code-based S-C and S-A associations in comparison to execution-based S-C and S-A associations. As discussed before, stronger S-C and S-A associations enabling us to execute responses automatically and fast are often desirable to allow us to save limited cognitive resources and still respond to environmental demands swiftly. When our previous learning experience is applicable to a current situation (i.e., when the same response is required as previously) strong, automatic S-C and S-A associations are therefore beneficial. However, when required responses change between situations, S-C and S-A associations might also interfere with responding (e.g., Horner & Henson, 2011, 2012), leading to performance costs. S-C and S-A associations strengthened by multiple task execution can lead to habitual responding that may sometimes be inappropriate and result in errors. The advantage of instruction-based S-C and S-A associations then is that they apparently enable automatic responding without strengthening automatic response tendencies to a degree that we cannot withstand them.

Finally, assuming that verbal code-based S-C and S-A associations really were qualitatively different from execution-based S-R associations, this would suggest that the memory structures underlying these two types of S-C and S-A associations, at least partially, differ. Prior studies suggested that both S-C and S-A associations are similarly

affected by time delays between prime and probe instances (i.e., similar temporal stability) and affect behavior for a comparable number of probe instances with switched S-C and S-A mappings (i.e., similar resilience against overwriting; Pfeuffer, Moutsopoulou et al., 2017). Furthermore, both verbal code-based S-C and S-A associations and execution-based S-C and S-A associations apparently contain abstract stimulus representations and thus generalize from one stimulus format to another (Pfeuffer, Hosp et al., 2017). These similarities led Pfeuffer, Moutsopoulou et al. (2017) to suggest that, although the impact of verbal code-based S-C and S-A associations was less pronounced, the memory structures and mechanism underlying execution-based and verbal code-based S-C and S-A associations might be similar. However, our findings are a first indication that the underlying memory structures and mechanisms of S-C and S-A retrieval may not be that similar after all. The present finding that the behavioral impact of execution-based, but not verbal code-based S-C and S-A associations, was modulated by the number of priming instances, suggests that there may also be substantial differences between the way execution-based and verbal code-based S-R associations are stored in and/or retrieved from memory. Future studies will have to determine the mechanisms underlying verbal code-based S-C and S-A retrieval to further elaborate on the differences and similarities of S-C and S-A associations formed on the basis of own action and verbal codes.

Overall, our findings confirm that instructions (i.e., verbal codes) allow us to learn and form automatic S-C and S-A associations that impact on our subsequent behavior. Instructions are therefore a powerful tool for establishing behavioral automatisms especially for stimulus-based actions that we cannot easily practice. Yet, when learning on the basis of instructions (i.e., when forming S-C and S-A associations based on verbal codes), in contrast to active task practice, it appears that there is no additional benefit from experiencing instructions multiple times.

Acknowledgements

This research was supported by a grant of the Deutsche Forschungsgemeinschaft (KI1388/5-1, Andrea Kiesel) and a grant of the Agence Nationale de la Recherche (SRA ANR-13-FRAL-0007-01, Karolina Moutsopoulou).

We thank Amelie Hörburger for her help with data collection.

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Table 1

The results of the 2x2x2 ANOVAs on probe trials reaction times (RTs) and percentages of errors (PEs) are displayed. Asterisks indicate significant effects.

	RTs	PEs
prime type	$F(1,38) = 34.26, p < .001, \eta_p^2 = .47 *$	$F(1,38) = 38.74, p < .001, \eta_p^2 = .51 *$
number of prime instances	$F(1,38) = 1.69, p = .202, \eta_p^2 = .04$	$F(1,38) = 2.95, p = .094, \eta_p^2 = .07$
classification	$F(1,38) = 143.24, p < .001, \eta_p^2 = .79 *$	$F(1,38) = 100.02, p < .001, \eta_p^2 = .73 *$
action	$F(1,38) = 31.19, p < .001, \eta_p^2 = .45 *$	$F(1,38) = 27.34, p < .001, \eta_p^2 = .42 *$
prime type X number of prime instances	$F(1,38) = 9.25, p = .004, \eta_p^2 = .20 *$	$F(1,38) = 20.09, p < .001, \eta_p^2 = .35 *$
prime type X classification	$F(1,38) = 66.83, p < .001, \eta_p^2 = .64 *$	$F(1,38) = 34.00, p < .001, \eta_p^2 = .47 *$
number of prime instances X classification	$F(1,38) = 23.78, p < .001, \eta_p^2 = .39 *$	$F(1,38) = 5.91, p = .020, \eta_p^2 = .14 *$
prime type X number of prime instances X classification	$F(1,38) = 10.63, p = .002, \eta_p^2 = .22 *$	$F(1,38) = 5.37, p = .026, \eta_p^2 = .12 *$
prime type X action	$F(1,38) = 24.31, p < .001, \eta_p^2 = .39 *$	$F(1,38) = 10.67, p = .002, \eta_p^2 = .22 *$
number of prime instances X action	$F(1,38) = 2.35, p = .134, \eta_p^2 = .06$	$F(1,38) = 4.95, p = .032, \eta_p^2 = .12 *$
prime type X number of prime instances X action	$F(1,38) = 4.92, p = .033, \eta_p^2 = .12 *$	$F(1,38) = 1.13, p = .294, \eta_p^2 = .03$
classification X action	$F(1,38) = 9.34, p = .004, \eta_p^2 = .20 *$	$F(1,38) < 1$
prime type X classification X action	$F(1,38) = 4.68, p = .037, \eta_p^2 = .11 *$	$F(1,38) < 1$
number of prime instances X classification X action	$F(1,38) < 1$	$F(1,38) = 1.26, p = .270, \eta_p^2 = .03$
prime type X number of prime instances X classification X action	$F(1,38) < 1$	$F(1,38) < 1$

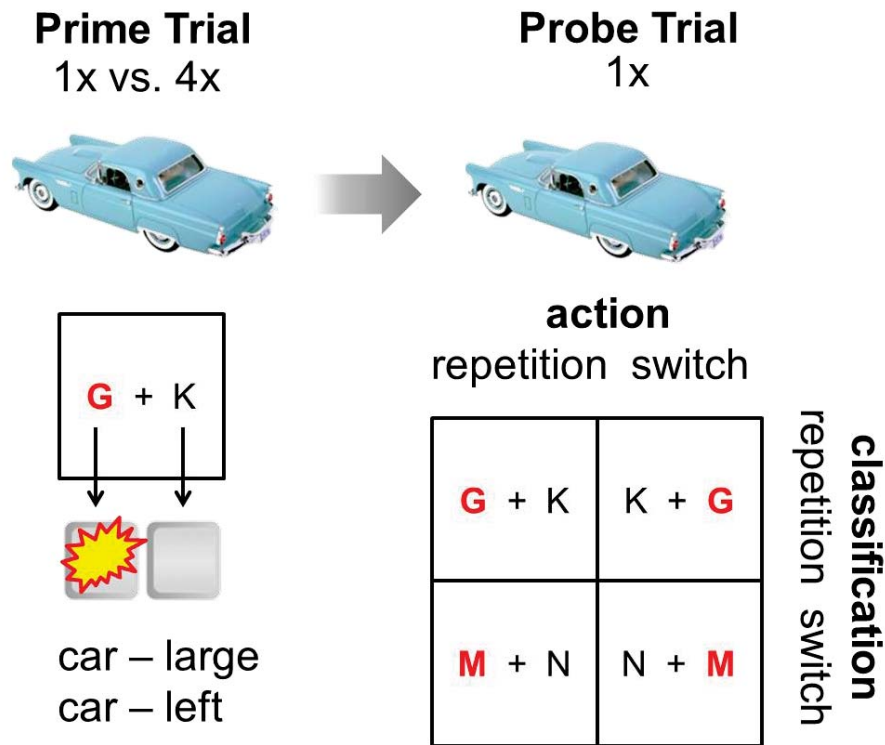


Figure 1. Schematic overview of the item-specific repetitions/switches in S-A and S-C mapping (i.e., action and classification mapping) between the prime instance(s) of a stimulus and its probe instance as indicated by the task cues (size task: “K + G” and “G + K” – K = “klein”/small, G = “groß”/large; mechanism task: “M + N” and “N + M” – M = “mechanisch”/mechanic, N = “nicht-mechanisch”/non-mechanic). S-A and S-C repeated across prime instances, but varied orthogonally between the item-specific prime instance(s) and probe instance. Each combination of classification and action mapping occurred equally frequently for the two prime types (executed and verbally coded) and the two numbers of prime instances (1 vs. 4). Correct classifications are marked as red and bold. Correct actions are indicated by the spatial position of the letter corresponding to the correct classification. Adapted from Pfeuffer, Moutsopoulou et al. (2017).

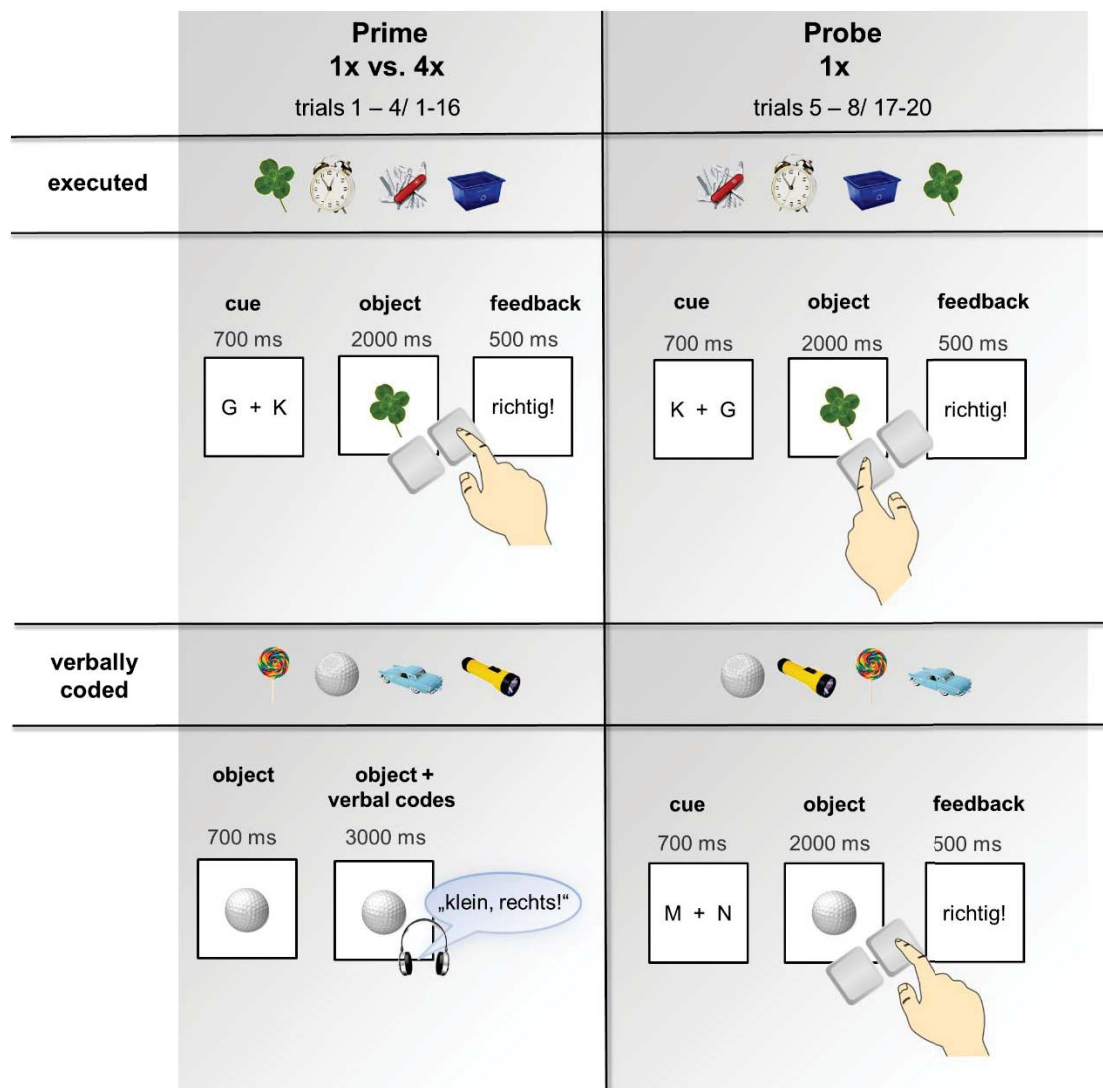


Figure 2. Structure of executed and verbally coded blocks. Objects were primed once or four times and probed once (2-7 trials lag between the prime/probe instances of an object). Participants actively classified objects in probe trials and executed prime trials by pressing the key spatially corresponding to the correct object classification. In verbally coded prime trials, verbal codes denoting class and action were presented while participants passively viewed the objects. Adapted from Pfeuffer, Moutsopoulou et al. (2017).

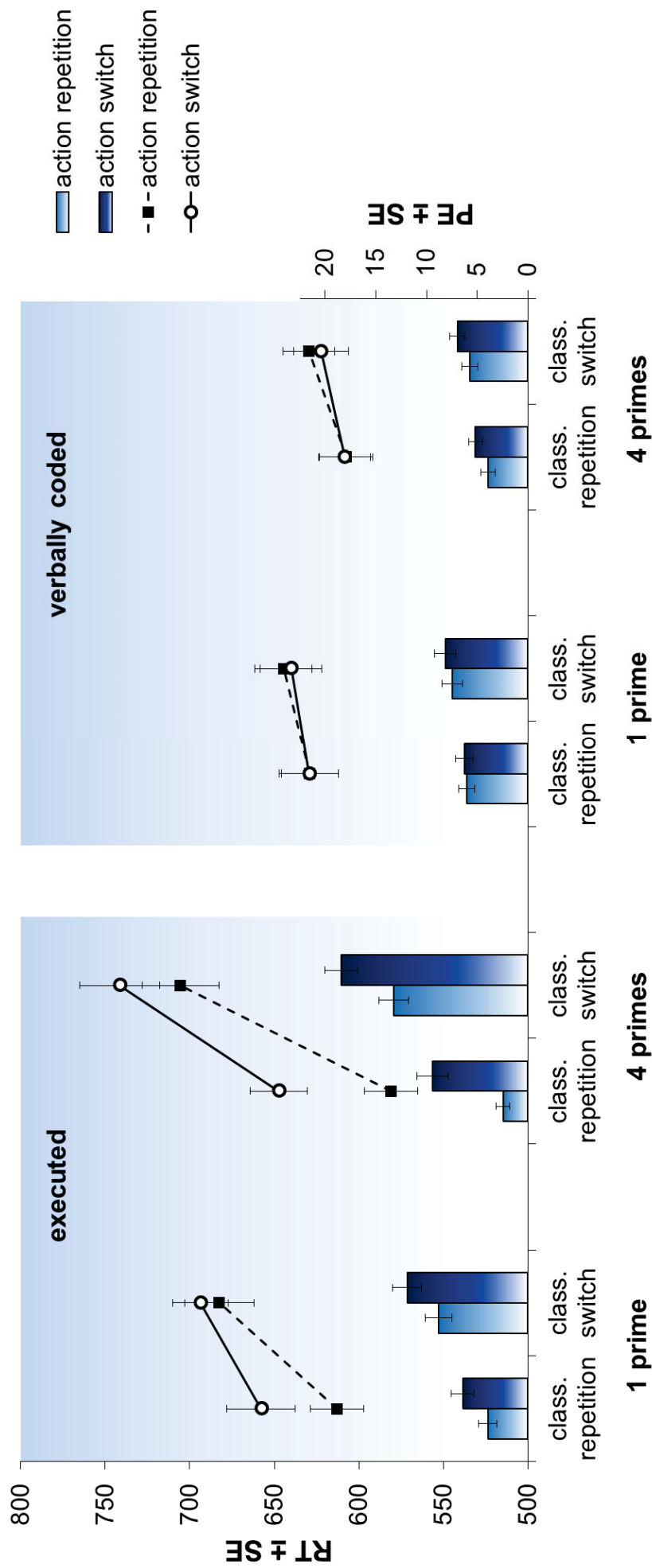


Figure 3. Mean reaction times (RTs in ms; lines) and percentages of errors (PEs in %; bars) in the probe trials displayed separately for the two prime types (executed vs. verbally coded), the two numbers of prime instances (1 vs. 4 primes) and the four possible switch conditions (classification: repetition vs. switch; action: repetition vs. switch). Error bars indicate standard errors.