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Selective directed forgetting of motor sequences

Markus Schmidt [a,*], Christian Frings [b], Tobias Tempel [a]

[a] *Ludwigsburg University of Education, Germany*
[b] *University of Trier, Germany*

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ABSTRACT

We examined selective directed forgetting in motor memory using a new variant of a three-list approach, to distinguish between accounts of directed forgetting. Participants consecutively studied three lists (L1, L2, and L3) of four sequential four-finger movements each. After studying L2, participants in the *forget group* were instructed to selectively forget the just studied four items of L2 but to retain the previously studied four items of L1, whereas the *remember group* did not receive any forget instruction for L2 but was encouraged to retain the items of both lists. In addition, we switched (*switch groups*) or repeated the items-enacting hand (*no-switch groups*) between L2 and L3 for a manipulation of post-forget-cue material competition for L2. A final memory test assessed recall performance for all three lists. Selective directed forgetting (lower L2 recall in the *forget group* as compared to the *remember group*) only occurred if the same hand was used for L2 and L3 (high interference between L2 and L3 encoding) whereas no selective directed forgetting occurred if the hand switched between L2 and L3 (low interference between L2 and L3 encoding). These results suggest that an inhibitory mechanism caused (selective) directed-forgetting costs that was triggered when items studied after the forget instruction had the potential to interfere with already stored items (i.e. were to be enacted by the same hand). When subsequently studied items pertained to the other hand no directed-forgetting costs occurred.

1. Introduction

Updating memory content is an important issue for everyday memory access. When stored information becomes outdated, a mechanism is necessary to weaken that outdated content and grant access on what is relevant now (e.g. a new telephone number after moving to a new apartment). Memory control comprises (among other things) intentionally forgetting no longer relevant information. Over decades, a multitude of studies has demonstrated the human ability for directed forgetting, using various kinds of item materials (for a review see MacLeod, 1998). However, there is a still ongoing debate in the literature about the underlying cognitive processes. A particularly strongly debated issue has been whether directed forgetting involves inhibition, that is, an active suppression of information that weakens subsequent accessibility. The present investigation addressed this question by adapting an experimental paradigm focusing on how selective effects of directed forgetting can be. Using sets of newly acquired motor sequences as items provided measures of directed forgetting that were of a non-verbal nature. Thus, a potential suppression of certain items was targeted at solely episodically defined categories, avoiding associations with semantic memory representations. This material, therefore, enabled a purer assessment of whether inhibition may be used intentionally to target specific items as compared to word materials that typically possess many associations to semantic and/or autobiographic memory. In addition, motor sequences allowed to test a specific assumption on the interference-dependence of inhibition by making use of body-based interference potentials (interference of movements performed with the same effector as opposed to a different effector, in particular).

A standard experimental paradigm for investigating intentional forgetting is the list method of directed forgetting (LMDF; Bjork, 1970). Participants in this paradigm typically study two word lists. After the first list, half of them are cued to forget this list (*forget group*), whereas the other half simply is informed about another upcoming list (*remember group*). Participants in the *forget group* are told, for example, that the computer program had a malfunction or that the first list just has been a “warming up”, and that the “real experiment” will start with the second list. In any case, the first list for them is cued to forget. Then all participants learn the second list. Memory for both lists is assessed in a final test, irrespective of the preceding instructions. Participants in the *forget*

* Corresponding author at: Ludwigsburg University of Education, Reuteallee 46, 71634 Ludwigsburg, Germany.
E-mail address: markus.schmidt@ph-ludwigsburg.de (M. Schmidt).

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group typically remember fewer items from the first list (*costs*) but show better memory performance for the second list (*benefits*) as compared to the *remember group*. This LMDF standard paradigm has found use in a multitude of studies across a wide variety of learning conditions and study materials (MacLeod, 1998). Despite the extensive use of the standard LMDF, this approach is relatively unspecific because the forget instruction entails a complete list, whereas updating memory content in everyday life is more often a specific process, targeting a specific to-be-forgotten content.

This issue of selectivity has been addressed by an adaption of LMDF, instructing the *forget group* only to forget one part of the so far encoded material but to remember the rest. A study by Sahakyan (2004) was the first to use a three-list variant of the LMDF paradigm. Participants were assigned to one of three conditions with different instructions: to remember all three lists, to forget list one but to remember list two and three, or to forget list two but to retain list one and three. They were initially told that they would study three word lists in succession for a later memory test and were informed that each list would be followed by an instruction that specifies whether or not that list is to-be-remembered. Results showed effective listwise forgetting but forgetting extended to list one when the forget instruction followed list two. Thus, no selective forgetting occurred but costs for both lists studied before the forget instruction.

In contrast, Delaney et al. (2009) demonstrated selective directed forgetting in a two-list approach containing relevant and irrelevant information within one list. Participants studied sentences about two characters, Tom and Alex, presented in an alternating order (e.g. "Tom watched television", "Alex brushed his teeth"). A subsequent forget instruction concerning only one of the two characters induced selective costs for the respective sentences in a recall test. This pattern of results has been replicated in several studies (Aguirre et al., 2020; Aguirre et al., 2014; Aguirre et al., 2017; Gómez-Ariza et al., 2013; for a failed replication however see: Storm et al., 2013).

Kliegl et al. (2013) scrutinized whether directed forgetting can be selective in a three-list design when employing short precue lists, whereas Sahakyan (2004) had used relatively long lists (twelve items each). Also different to the Sahakyan (2004) study, where each list was followed by its cue instruction, *forget group* participants here were cued after L2 to forget L2 and to keep remembering L1. In addition, Kliegl et al. (2013) scrutinized whether selectivity in the three-list task varies with the level of discriminability of the precue lists L1 and L2, "assuming that with a high level of discriminability between the irrelevant precue list and the relevant precue list, selectivity may be high, and with a low level of discriminability, it may be low" (p. 454). Categorical features to vary lists discriminability were the font color of the items (Experiment 1) and the auditory presentation of the two lists by either the same voice or two different voices (Experiment 2). Moreover, they wanted to examine whether selectivity in directed forgetting differs between the three-list and the two-list task (Experiment 3). Kliegl et al. (2013) were the first to demonstrate selectivity in a three-list task. Selective costs for only the second but not the first list were observed, independently of modality of item presentation, the level of discriminability of the precue lists, or the type of the LMDF task used (see also: Kliegl et al., 2018).

1.1. Competing explanations for selective directed forgetting

The question of when and under which circumstances there will be selective directed forgetting costs pertains to the explanatory models of LMDF. The selective-rehearsal account (Bjork, 1970), as the first prominent (one-factor) model, assumed forget-cued participants to selectively rehearse (only) the to-be-remembered items, thereby producing the costs (and the benefits). In contrast, the retrieval-inhibition account (Geiselman et al., 1983) assumes costs to be produced by active inhibitory (executive) control processes, impairing access to the forget-list items. Finally, the context-change account (Sahakyan & Kelley, 2002) states that the forget cue induces a mental context change that impairs recall of the forget list at test due to a contextual mismatch between the encoding and the retrieval context. Recently, also two-factor models have been suggested, assuming the costs being caused by inhibition or context change, whereas the benefits (partly) reflect improved encoding (Pastötter et al., 2012; Sahakyan & Delaney, 2003).

Thus, seen from the more recent two-factor perspective, the question of selectivity in directed forgetting costs in LMDF is the question about inhibition and/or context change as the cause, i.e. a challenge for research is to disentangle the relative contributions of the assumed mechanisms. In fact, there are quite a number of selective directed forgetting studies that already have provided evidence for the inhibitory view. Gómez-Ariza et al. (2013) and Aguirre et al. (2014), using Delaney et al.'s (2009) stimuli and procedure, observed selective directed forgetting in their control samples for uncommon populations (adolescents diagnosed with social anxiety disorder and older adults). Both studies were motivated by the inhibitory assumption, that only the to-be-forgotten items will be targeted by the selective forgetting mechanism. Aguirre et al. (2017) also showed reliable selective directed forgetting in support of the idea of a flexible goal-oriented executive control mechanism just suppressing irrelevant precue information. Kliegl et al. (2018) were first to show, that selectivity in directed forgetting develops later during childhood and adolescence than nonselective directed forgetting, a result in line with the inefficient inhibition hypothesis of development (Bjorklund & Harnishfeger, 1990).

Two of the three explanatory models make the same predictions about selective directed forgetting costs in a three-list variant of LMDF, given the second list is to-be-forgotten and the first and third list are to-be-remembered. The selective-rehearsal account predicts selective directed forgetting costs in this variant of LMDF because it claims that irrelevant memories are omitted from the rehearsal process. Participants should rehearse solely the relevant items, – regardless of their serial list position. The retrieval-inhibition account assumes the to-be-forgotten items (not only in this variant) as one subset of information and the to-be-remembered items as another one. So, one subset may uniquely become a target for active inhibition, in favor of the other, caused by the task demands (to forget L2). From the inhibitory view selective directed forgetting costs accordingly also should emerge in this variant. They could be seen as caused by an intentionally driven (inhibitory) control process, with the inherent assumptions that inhibition can selectively target specific memory contents and that it serves the purpose to enhance memory for to-be-remembered information (cf. Anderson, 2005). The context-change account, in contrast, assumes that a forget instruction triggers a mental context change, thereby lowering accessibility of all information studied before the forget instruction. Therefore, it predicts no selectivity of costs in this variant. Both precue lists - L1 and L2 - should be equally affected by the contextual encoding-retrieval mismatch, due to the forget-cue-elicited context change (after L2 encoding). Selective costs for the second list in the absence of costs for the first list, therefore, could not be explained in terms of the context-change account.

1.2. The present study

To sum up, two of the three explanatory models of directed forgetting predict selectivity of costs in the three-list task of LMDF. However, an adaptation of this experimental paradigm for the use of motor sequences as item material allows us to distinguish between all three explanatory models in a novel way. Newly acquired sequential finger movements are of non-verbal nature and memorization takes place in solely episodically defined categories. Associations to semantic and/or autobiographic memory are much less likely than for words. This material, therefore, allowed to manipulate the degree of interference between item lists independently from such associations but based on properties of the effectors involved in movement execution.

According to the inhibition theory by Anderson (2005), inhibition may follow the same principles across different memory phenomena (such as retrieval-induced forgetting and directed forgetting), one of them being interference dependence: Information is only inhibited when it has the potential to interfere with to-be-remembered content. With regard to directed forgetting this primarily concerns items studied after receiving a forget instruction and, correspondingly, it has been shown that no directed forgetting costs occur when there is no more item material to be studied or it is of insufficient amount (e.g. Conway et al., 2000; Pastötter & Bäuml, 2007, 2010). Here, we did not manipulate the interference potential in terms of the amount of post-cue studying but by either assigning the same or a different effector to movement execution, assuming a higher level of interference between motor sequences performed with the same hand as between motor sequences performed with opposing hands. Thus, we designed a particular motor modification of the LMDF task, that allowed us for distinguishing the final recall contribution between all three prominent accounts of LMDF.

Research on directed forgetting in motor memory is rare. Burwitz (1974) examined proactive interference and directed forgetting in short-term motor memory. Sahakyan and Foster (2009) compared directed forgetting for self-performed action phrases with verbally learned action phrases and found equivalent directed forgetting impairments for both. Most importantly for the present study, Tempel and Frings (2016) examined directed forgetting of motor sequences. They conducted two experiments, adapting the list method for sequential finger movements as item material in a two-list approach. Each sequential finger movement consisted of four consecutive key presses from three fingers of the right hand. In this study, costs only emerged in Experiment 2, whereas there was a beneficial effect for L2 recall in the forget group in both experiments, suggesting that benefits were not a mere byproduct of costs. In contrast to Experiment 1, Experiment 2 involved a three-minute break between L1 and L2 along with different response keys for L2 as for L1. Perhaps, these changes facilitated an internal context change, thus producing directed forgetting costs. Alternatively, an inhibition of L1 might have been facilitated because the break and new response keys enhanced discriminability of the to-be-inhibited item set.

Here, we set out to examine whether directed forgetting could be selective in motor memory, using a particular three-list approach. Akin to Kliegl et al. (2013) we created three short sets (the lists) of four sequential finger movements, with each single finger-movement sequence (the item) consisting of four consecutive finger movements of the index, middle and ring finger of the left or the right hand (see Appendix A). Akin to Sahakyan (2004), each list presentation was followed by the lists' cue. L1 was to-be-remembered always. After learning of L2, participants either received a *forget* or a *remember* cue instruction for that list before they proceeded with L3. L3 also was to-be-remembered always. Yet, what is more, it has been shown that directed forgetting costs only occur if a forget instruction is followed by a sufficient amount of additional study of new material (Conway et al., 2000; Pastötter & Bäuml, 2007, 2010), suggesting that there must be a certain amount of interference between the to-be-forgotten and new information. With motor material, such interference probably is at a maximum when the same effector has to be used. Therefore, we manipulated interference between L2 and L3 by repeating (*no-switch group*) or switching (*switch group*) the lists enacting hand between L2 and L3 (see Fig. 1).

Using this particular motor task modification of the LMDF paradigm provides a tool for distinguishing between the three prominent accounts of LMDF. The results of the current experiment can differentiate between all three explanatory hypotheses: Finding non-selective directed

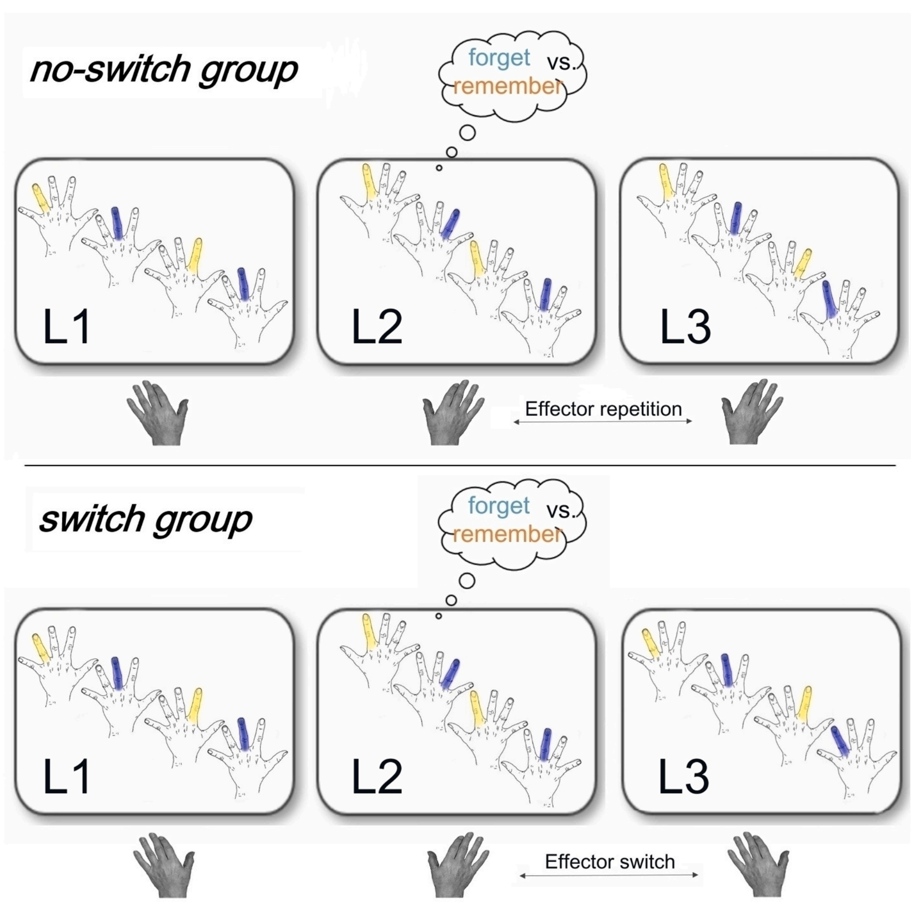

Fig. 1. Scheme of the experimental design including the first item of each of the three lists L1, L2 and L3 (see Appendix A for the complete lists). First experimental factor was effector repetition (*no-switch groups*) or effector switch (*switch groups*). Second experimental factor was the *remember* or *forget L2* instruction. This design resulted in four different experimental groups.

forgetting costs of both - L1 and L2 - favors the context-change account, for the reason of the assumed (internal) contextual change due to the forget instruction after L2 learning. Finding selective directed forgetting costs for L2 only in the absence of an effector change (*no-switch group*) speaks in favor of the inhibition account, for the reason of the inhibitory account assumed necessary amount of interference between the to-be-forgotten and new information (cf. Anderson, 2005). And finally, finding selective directed forgetting regardless of whether there is an effector change or not favors the selective-rehearsal account.

Our hypothesis was to find support for the assumption that inhibition is involved in directed forgetting. Considering recent evidence in favor of the inhibitory view (Aguirre et al., 2020; Kliegl et al., 2018), we expected an interaction of effector switch and forget-instruction for L2 memory performance, whereas L1 memory was expected not to depend on the L2 forget-instruction.

2. Method

2.1. Participants

One-hundred-and-forty-four psychology students (mean age = 22.1) at the University of Trier participated in the experiment. They either received course credit or were paid six Euros for their participation.

2.2. Design

Two factors were manipulated between participants: effector switch after L2 (*no-switch* or *switch group*) and the instruction after studying L2 (*remember* or *forget group*).

2.3. Material

The experiment was conducted using Dell Optiplex 755 PCs with Eizo FlexScan S1901 monitors and standard German QWERTZ keyboards. The software PXLab (Irtel, 2007) served for running the experiment. The items comprised a total of twelve four-finger movements of the index-, middle-, or ring finger, in three sets of four items (L1, L2 and L3) for each participant. Across all conditions, L1 was to be enacted with the left hand always, L2 was to be enacted with the right hand always. Depending on the respective group assignment (see Fig. 1 or Appendix A), L3 items were enacted either with the right hand (*no-switch groups*) or with the left hand (*switch groups*). The four-finger movements were to be enacted on the second lower row of the keyboard, same keys for left- or right-hand enactment (keys were V, B, and N). During the learning phase, the lists were announced in numbers for 5 s (e.g. "now upcoming part 1 of the experiment"), then the participants were instructed to lay their three corresponding fingers of the (explicitly named) respective list hand on the three marked keys. Starting the list presentation by mouse clicking a checkbox, 3 s blank screen were followed by an animation of the first four-finger movement (= item). At the beginning of the animation, a drawing of the corresponding hand appeared for 1000 milliseconds (ms). Then, an animation of the hand showed four consecutively flashing fingers (the first finger was colored yellow, second finger was colored blue, the third finger was colored yellow again, the fourth finger was colored blue again, 200 ms per flash and 200 ms for the uncolored hand drawing between the fingers). Once the animation disappeared, participants could perform it immediately by sequentially pressing the four corresponding keys. Feedback about the performed sequence was given, fostering encoding accuracy. Wrong finger movements (key presses) were indicated by displaying: "Fehler!" (English: "Error!") in the center of the screen. After 3 s, the next trial started (see Fig. 2).

2.4. Procedure

The experiment consisted of three phases: learning, distractor task and final memory test. First, general instructions were given on the computer screen and summarized by the experimenter. Participants were informed about three upcoming parts (lists) of the experiment, each followed by an instruction to either forget or to remember the four sequences of that list for a final memory test. The experimenter ensured the comprehension of the task verbally. The participant then was onscreen informed about the upcoming part of the experiment (i.e. the list number) and told to place the respective three fingers (left hand or right hand) on the response keys. Clicking a checkbox started the list presentation. Participants had to consecutively press four keys in response to an animated hand movement graphic illustrating the item, that is, the order in which the four fingers were to be moved. Fifteen cycles per list were presented, each one containing the four items of that list in a random order. So, participants had sixty learning trials per list. Once the fifteen randomized cycles of the list's four items were finished, participants either received a remember or a forget instruction for this list, together with an indication of 30 s for rest and bodily relaxation before the next list. All three lists were given consecutively, always followed by the lists` cue instruction and the thirty-second break. L1 always was to be enacted with the left hand, L2 always was to be enacted with the right hand. So, in all four experimental groups there always was an effector switch from L1 to L2, enhancing list discriminability. L1 and L3 instructions for both lists in all four experimental groups always were to-be-remembered, the experimental groups differed only in the post-list cue instruction for L2 and the enacting hand for L3. One group received to-be-remembered instruction for L2 and enacted L3 also with the right hand (*no-switch - remember group*), the second group received to-be-forgotten instructions for L2 and enacted L3 also with the right hand (*no-switch - forget group*), see the upper section of Fig. 1. The remaining two experimental groups (i.e. the lower section in Fig. 1) also varied in the L2 instructions (remember or forget), but both groups enacted L3 then with the left hand. So, the third group received to-be-remembered instruction for L2 and enacted L3 with the left hand (*switch - remember group*), the fourth group received to-be-forgotten instructions for L2 and enacted L3 also with the left hand (*switch - forget group*). Forget-cued participants were post list cued that it was important to try to forget all the just learned sequences of List 2. Remember-cued participants just were encouraged to keep the lists in mind. We counterbalanced the assignment of the item sets to the list positions, resulting in six different order variations (counterbalanced between participants).

The final test phase encompassed three consecutive memory tests for all three lists in the order of their study. After a three-minute distractor task (a Sudoku puzzle) following the L3 thirty-second break, participants were informed about a now upcoming final memory test. Then instructions for L1 recall appeared. Participants were cued for the list recall by the displayed list number and instructed to place the corresponding hand (the same hand used during encoding) on the three response keys. They were instructed to type in all the four sequences of the cued list in any order they came to mind, but with the intention to type in all four items of the list. They were encouraged to guess, if they could not remember all four list items, because the computer expected the input of a four-finger sequence for four times before continuing. Then, an exclamation mark indicated to enter the first sequential four-finger movement (i.e. one item) of that list that came to mind. After pressing four different response keys (i.e. input of a sequential four-finger movement), 3 s blank screen followed, then the next exclamation mark indicated to enter the next sequential four-finger movement. After participants completed (all four) entries, the next list instruction appeared, indicating again the list number and prompting participants for the placement of the list hand (i.e. the same hand used during encoding) fingers on the response keys. Instructions for L2 recall told participants in the forget groups that they should recall all L2 items, despite the opposite instruction to forget them after L2 encoding. Then the four exclamation marks again indicated to type in all four sequences of that list in any order they came to mind, but four items had to be typed in. This procedure was repeated until all twelve items in all three lists were tested. Recall for each particular item was scored correct, if all four

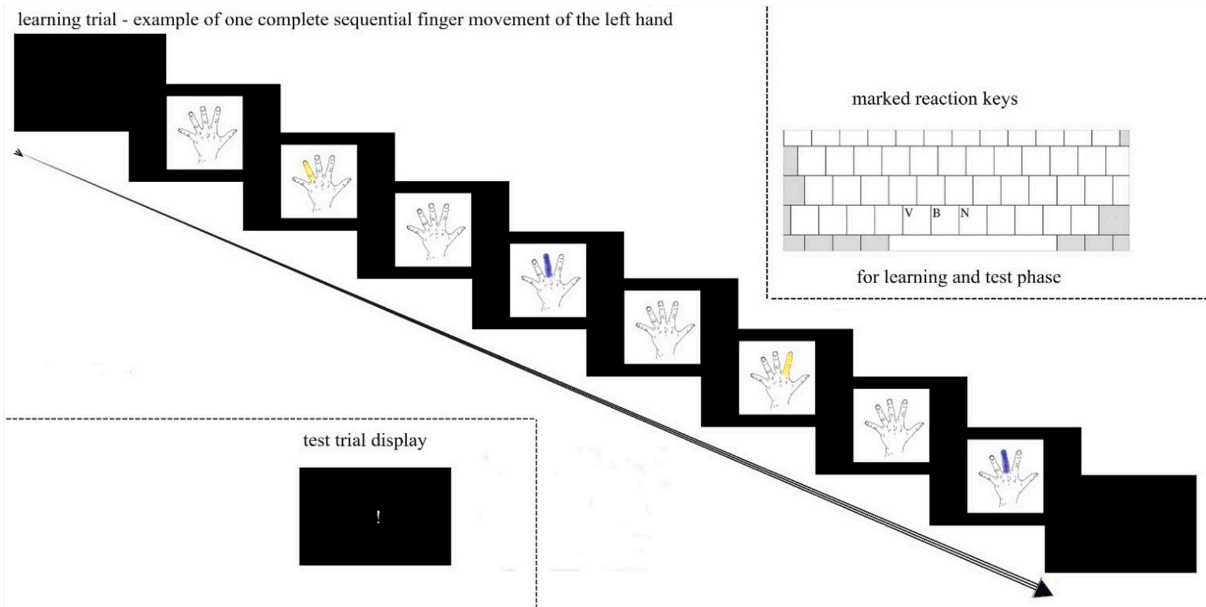

Fig. 2. The main section depicts a trial in the learning phase of L1 for item 1. It starts with a blank screen display for 3 s. Then a drawing of the left hand is given. After further 1000 ms, the first finger illuminates yellow for 200 ms, then the second finger illuminates blue for 200 ms, the third finger illuminates yellow again for 200 ms, finally the fourth finger illuminates blue for 200 ms again. Between the colored fingers, the uncolored drawing of the hand is given for 200 ms. The displayed hand subsequently disappears, and the participant is instructed to then enter the sequential finger movement just illustrated (right upper section shows the response keys for learning and test). After the sequence input, feedback for wrong key sequences was given, then the routine starts again for the next item. The left lower section shows the displayed exclamation mark in the test phase prompting for the input of a sequence. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

key presses of that item were correct (see Appendix A), whereas the input order of the items was irrelevant.

3. Results

Recall performances for the three lists were examined in three 2 (post-L2 instruction: forget, remember) x 2 (effector switch after L2, no effector switch after L2) ANOVAs. Regarding L1, there was no significant main effect nor interaction, $F(1, 140) < 2.18$, $p > .142$, $\eta_p^2 < 0.015$. Thus, L1 remained unaffected by either the forget instruction or an effector switch (see Fig. 3).

Regarding L2, the main effect of post-L2 instruction was not significant, $F(1, 140) = 0.46$, $p = .498$, $\eta_p^2 = 0.003$, neither was the main effect of effector switch, $F(1, 140) = 2.52$, $p = .115$, $\eta_p^2 = 0.018$, but there was a significant interaction, $F(1, 140) = 6.21$, $p = .014$, $\eta_p^2 = 0.042$. Simple effects analyses showed that the forget group without effector switch after L2 (*no-switch - forget group*) recalled significantly fewer L2 items than the remember group without effector switch after L2 (*no-switch - remember group*), $F(1, 140) = 5.03$, $p = .026$, $\eta_p^2 = 0.035$, whereas forget (*switch - forget group*) and remember groups with effector switch (*switch - remember group*) did not differ significantly, $F(1, 140) = 1.64$, $p = .202$, $\eta_p^2 = 0.012$ (see Fig. 3). Thus, directed forgetting costs for L2 only occurred when the effector did not change from L2 to L3 (*no-switch group*).

Furthermore, a post hoc comparison between L1 and L2 recall in the *no-switch - forget group* showed a reliably lower recall for L2 compared to L1 recall in that group, $t(35) = 3.08$, $p = .004$, Cohen's d = 0.514. A post hoc comparison between L1 and L2 recall in the *no-switch - remember group* showed no such reliable difference between L1 and L2 recall, $t(35) = -0.43$, $p = .672$, Cohen's d = −0.071. Post hoc comparisons between L1 and L2 recall in the *switch - forget group* did not show reliable difference either, $t(35) = 0.28$ $p = .78$, Cohen's d = 0.047, nor did post hoc comparisons between L1 and L2 recall in the *switch - remember group*, $t(35) = -0.34$ $p = .74$, Cohen's d = −0.056. So, selective directed forgetting costs for L2 occurred, i.e. L2 recall in the *no-switch - forget group* was reliably lower than L2 recall in the *no-switch - remember group* (see Fig. 3) and *also* was reliably lower than L1 recall in the same (*forget*) group, − but *only* when the effector did not switch between L2 and L3[1] (*no-switch group*).

Regarding L3, there was no significant main effect of effector switch nor an interaction, *Fs* < 1, but a significant main effect of post-L2 instruction, $F(1, 140) = 7.73$, $p = .006$, $\eta_p^2 = 0.052$. The forget groups recalled more L3 items than the remember groups, reflecting directed-forgetting benefits for L3.

4. Discussion

Results are in line with an inhibitory account of directed forgetting costs. An instruction to selectively forget one of two previously studied sets of motor sequences caused decreased memory accessibility of that set when it was to be enacted with the same effector as a subsequently studied set of motor sequences (*no-switch groups*), but not when the subsequently studied set involved a different effector (*switch groups*). The occurrence of selective directed forgetting when the effector did not switch after L2 together with its absence when the effector did switch points to an adaptive inhibitory mechanism that serves to resolve competition between item sets as the cause of selective directed forgetting costs.

Participants consecutively learned three lists of sequential finger movements. The use of different hands for L1 and L2 in all experimental groups was intended to maximize list discriminability, thus, potentially facilitating targeted inhibition. L3 also used the right hand for the lists sequence enactment (*no-switch groups*) or switched sequence enactment

[1] Given the possibility that recall might get affected by the participants dominant hand, we conducted an ANOVA for L2 recall with the dominant hand (left, right) as an additional control factor. This control factor did not moderate the significant interaction effect between effector switch and instruction regarding L2 recall, $F(1, 136) = 1.14$, $p = .288$, $\eta_p^2 = 0.008$.

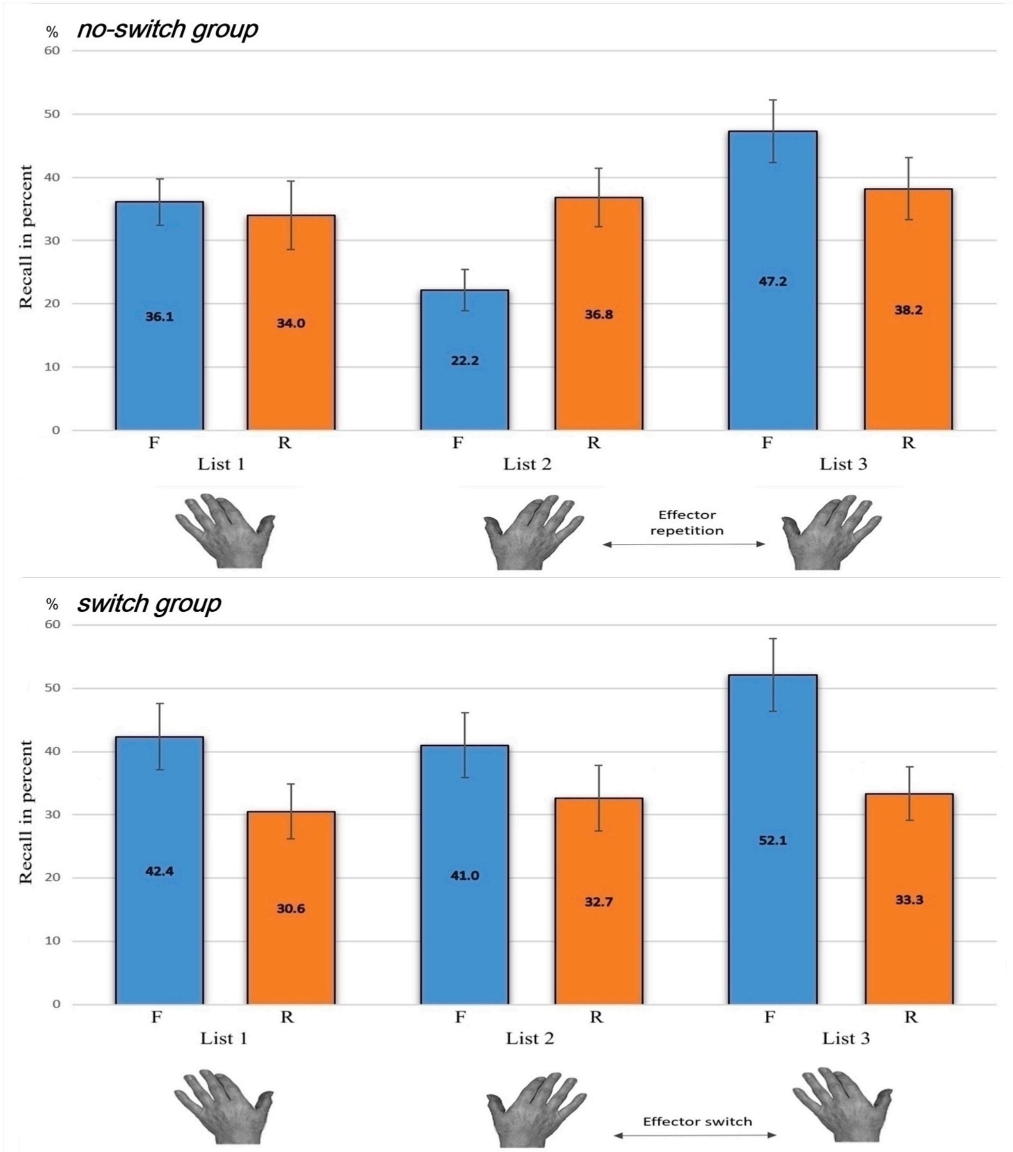

Fig. 3. Recall performance in percent for the three lists in the forget (F) and remember (R) conditions for same effector L3 as L2 (upper section – *no-switch group*) and switched effector from L2 to L3 (lower section – *switch-group*). Error bars represent ±1 S.E.M.

back to the left hand (*switch groups*). Only without effector switch after L2 (*no-switch groups*), L2 recall was reliably lower in the *forget group* than in the *remember group*, and L1 recall in the *forget group* was reliably higher than L2 recall in the *forget group* (i.e. selective directed forgetting costs occurred). Thus, our results demonstrate selective directed forgetting in motor memory for the first time. Moreover, L1 recall did not differ significantly between the *remember* and *forget* groups, which is incompatible with the assumption of a mental context change accounting for directed-forgetting costs. If the forget cue would have induced a context change, L1 recall should have been affected as well. The context-change account predicts no selectivity of costs for our LMDF variant, because both precue lists - L1 and L2 - should be equally affected by the contextual encoding-retrieval mismatch, due to the forget-cue-elicited context change. Selective costs for the second list in the absence of costs for the first list (as observed in the *no-switch groups*) cannot be explained in terms of the context-change account.

Furthermore, concerning the remaining prominent explanatory model of directed forgetting, the selective-rehearsal account (Bjork, 1970) predicts for the present experimental design, that forget-cued participants solely should rehearse the items of L1 and L3, no matter whether they were enacted with the left or the right hand. Thus, the selective-rehearsal account can explain the observed selective directed forgetting for the *no-switch group* but cannot explain its absence when the effector switched from L2 to L3. Evidence against selective rehearsal as being the cause of selective directed forgetting also comes from a recent study by Aguirre et al. (2017). In their Experiment 1, they manipulated working-memory load. Selective directed forgetting was observed under an articulatory suppression condition, suggesting “that selective rehearsal might not play a key role in producing SDF” (p.5).

Switching the effector after L2 examined whether reducing interference between L2 and L3 (by the assignment of a different hand to L3) would reduce directed forgetting costs. We assumed the change of the enacting hand to involve less or no competition at all between L2 and L3. No selective nor non-selective directed forgetting costs occurred in the *switch group*, suggesting that directed forgetting costs only occur if subsequent encoding involves a sufficient amount of competition with the precue material.

The observed absence of a cost effect when the effector changed after L2 corresponds to the idea of an adaptive inhibition mechanism, able to target a specified item set, – if this set has the potential to compete with the encoding of a novel item set. This in turn corresponds to a general inhibitory account of directed forgetting, assuming inhibition to be a (voluntary) goal-oriented executive-control mechanism resolving interference between memory contents (Anderson, 2005; Anderson & Hanslmayr, 2014; Bäuml et al., 2008; Geiselman et al., 1983; Hanslmayr et al., 2012). Inhibition should arise only if there is postcue encoding of competing (i.e. interfering) material and, correspondingly, it has been shown that no costs occur if the forget cue is followed by an insufficient amount of additional new learning material (Conway et al., 2000; Pastötter & Bäuml, 2007, 2010). This ultimately points on inhibition as being the cause of costs, resolving interference between memory contents, serving the purpose to enhance memory for to-be-remembered information (cf. Anderson, 2005). Perhaps, a modification of existing non-inhibitory accounts might be able to explain the present findings, but in a comparison of the theories presently existing in the literature our results clearly favor inhibition theory.

In the learning phase, the items of each list were executed by the same fingers of the same hand. Thus, the hand can be regarded as a cue organizing storage of the finger movements in memory. The hands have been used in a corresponding manner (i.e. for categorization of motor sequences) in previous research, in particular in studies on retrieval-induced forgetting. This memory phenomenon occurs when the selective retrieval of a subset of information causes forgetting of the non-retrieved rest of information from that set. Tempel and Frings (2013) demonstrated this effect in motor memory. After participants had studied two sets of sequential finger movements (one performed with fingers of the left hand, the other with fingers of the right hand), retrieval of only half the items of one hand induced forgetting for the other half of items of that hand. Recall in a final memory test was lower as compared to recall of items from the opposite hand. This finding together with results from subsequent studies (Tempel et al., 2016; Tempel & Frings, 2014a, 2014b, 2015, 2017) suggests that an inhibitory mechanism caused the observed retrieval-induced forgetting, resolving interference that arises during selective retrieval among the items of one set. Whereas retrieval triggered interference among items of the same hand, no interference occurred between items of the two hands, however. Thus, research on retrieval-induced forgetting shows that the hands can be used to organize storage of sequential finger movements in distinct categories.

Regarding the fact that participants in the test phase were encouraged to guess if they could not remember all four sequences of the respective list, it is possible that implicit memory also contributed to their recall performance. Even without being able to consciously recollect an item, the correct motor sequence might have been produced at a level above chance in a few instances. However, given the explicit structure of our experiment and the explicit (conscious) directed forgetting instruction, we do not believe that such implicit memory recall contributions would have been able to substantially affect the effects of directed forgetting that were of interest here. Moreover, research showed that implicit memory also can be affected by directed forgetting (e.g. MacLeod, 1989).

In everyday motor behavioral situations, this interference resolving effect of selective directed forgetting might be observed as well. Imagine, for example, the situation of practicing to serve in a tennis match. The effects of interference from previous serving habits may result in actual goal errors when one is confronted with new task demands, e.g. in form of a faster than usually reacting tennis partner. Selectively forgetting this behavioral subset of habitually targeting a certain point on the line in the opponent's field and replacing this subset with a new serving behavioral subset targeting a different than usually point may rely on this (voluntary) goal-oriented executive-control mechanism resolving interference in motor memory.

Publicly available data set

https://osf.io/89h4p/?view_only=bd24c1fd0a174ce384edc798f21511c8.

Declaration of competing interest

The authors have no conflicts of interests to declare.

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Appendix A

Motor sequence items of the three lists respective to the group assignment including the F(orget) vs R(emember) list cue for the no-switch groups:

Set	Item	First finger	Second finger	Third finger	Fourth finger	Enacted by	List cue
L1	1	Ring finger	Middle finger	Index finger	Middle finger	Left hand	R
L1	2	Middle finger	Ring finger	Middle finger	Index finger	Left hand	R
L1	3	Index finger	Middle finger	Index finger	Middle finger	Left hand	R
L1	4	Index finger	Ring finger	Middle finger	Ring finger	Left hand	R
L2	5	Index finger	Ring finger	Index finger	Middle finger	Right hand	F vs R
L2	6	Middle finger	Index finger	Middle finger	Index finger	Right hand	F vs R
L2	7	Middle finger	Ring finger	Index finger	Ring finger	Right hand	F vs R
L2	8	Ring finger	Index finger	Middle finger	Ring finger	Right hand	F vs R
L3	9	Index finger	Middle finger	Ring finger	Index finger	Right hand	R
L3	10	Index finger	Ring finger	Index finger	Ring finger	Right hand	R
L3	11	Middle finger	Ring finger	Index finger	Middle finger	Right hand	R
L3	12	Ring finger	Middle finger	Ring finger	Index finger	Right hand	R

and the
switch groups:

Set	Item	First finger	Second finger	Third finger	Fourth finger	Enacted by	List cue
L1	1	Ring finger	Middle finger	Index finger	Middle finger	Left hand	R
L1	2	Middle finger	Ring finger	Middle finger	Index finger	Left hand	R
L1	3	Index finger	Middle finger	Index finger	Middle finger	Left hand	R
L1	4	Index finger	Ring finger	Middle finger	Ring finger	Left hand	R
L2	5	Index finger	Ring finger	Index finger	Middle finger	Right hand	F vs R
L2	6	Middle finger	Index finger	Middle finger	Index finger	Right hand	F vs R
L2	7	Middle finger	Ring finger	Index finger	Ring finger	Right hand	F vs R
L2	8	Ring finger	Index finger	Middle finger	Ring finger	Right hand	F vs R
L3	9	Ring finger	Middle finger	Index finger	Ring finger	Left hand	R
L3	10	Ring finger	Index finger	Ring finger	Index finger	Left hand	R
L3	11	Middle finger	Index finger	Ring finger	Middle finger	Left hand	R
L3	12	Index finger	Middle finger	Index finger	Ring finger	Left hand	R

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