Binding and Retrieval of Temporal Action Features:

Probing the Precision Level of Feature Representations in Action Planning

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Abstract

The duration of an action can be critical to accomplish specific goals. Empirical findings and theoretical considerations suggest that different stages of action planning and execution require different specification levels of action features. It is assumed that at first only crude categorical features are integrated into action plans, which are then specified by subsequent sensorimotor processes during action execution based on situational conditions. In two experiments, we investigated if the integration of action duration into action plans indeed relies exclusively on categorical duration representations or also on continuous metric representations. Participants responded to visual prime and probe stimuli with short and long key presses. The duration of the prime response was indicated by a previous response cue, the duration of the probe response was indicated by the shape of the probe stimulus. Analyses of response durations revealed that for response category repetitions from prime to probe, the actual durations of the repeated responses were more similar for shape repetitions than for shape switches. This indicates that continuous temporal information is integrated into an action plan and subsequently retrieved by stimulus repetition. Our results suggest that action duration is integrated into the action plan in a relatively precise form at an early stage of action planning.

Keywords: feature binding; stimulus-response binding; response duration, continuous features; action control

Public Significance Statement

Empirical findings and theoretical considerations suggest that different stages of action planning and execution require different specification levels of action features. It is assumed that at first only crude categorical features are integrated into action plans, which are then specified by subsequent sensorimotor processes during action execution based on situational conditions. This study provides evidence that continuous action features are integrated into action plans in an already relatively precise form at an early stage of action planning.

Binding and Retrieval of Temporal Action Features:

Probing the Precision Level of Feature Representations in Action Planning

Timing is key in human action control. This includes at least two components: the timepoint of initiating an action and the duration of the action. In many everyday situations the duration of an action is the decisive component for achieving an action goal. For example, with common smartphones or tablets, a short button press activates the screen saver, while a long button press initiates the power-off process. In addition to this crude categorical distinction of short vs. long action duration, each action realizes a specific metric duration. Sometimes, this metric component has direct consequences, too, e.g., when gradually dimming the room light or controlling the volume of a stereo. But even if a specific metric duration is not intended, actions still vary on a graded continuum of different durations. Here we asked how this seemingly irrelevant feature of metric action duration is represented in actions that are defined in temporal categories of short and long. Crucially, these categorical versus metric representations likely serve different purposes in action control. While categorical distinctions are relevant for deciding between different potential goals, metric duration is especially relevant during action execution, e.g., when monitoring successful completion of an action. For example, when coordinating an action with another person, such as handing over an object, it is important to adjust the duration of one' s own action to the action of the other person in order to avoid dropping the object or inefficiently delaying the accomplishment of the goal. Similar constraints arise for any motor interaction with the physical environment. The role of categorical and metric features for human action representations is only poorly understood at present, however.

Theoretical frameworks of human action representation suggest that action plans involve temporary bindings between representations of action features (Hommel, 2009; Jeannerod, 1999; Keele et al., 1990; Stoet & Hommel, 1999). These bindings contain not only action-related feature codes, but also feature codes of stimuli in the agent’s environment during an action episode (Frings et al., 2020; Frings et al., 2007; Hommel, 1998; Pfister, 2019). As an example, planning a response to a circular stimulus with a right-hand key press involves a binding between the stimulus-feature "circular shape" and the action feature "right hand". The existence of such feature bindings has been repeatedly demonstrated by the observation that repeating some but not all of the features of a previous action episode yields performance costs compared to both repeating all features or alternating all features (so-called partial repetition costs; for reviews, see Frings et al., 2020; Henson et al., 2014; Hommel, 2004). This observation suggests that repeating one of the bound features (e.g., repeating the circular shape of the stimulus) retrieves the other bound feature codes (e.g., the "right hand" feature of the response), which causes conflict when the current situation requires a different combination of feature codes (e.g., responding to a circular shape with a left-hand key press).

Although research on binding and retrieval has primarily capitalized on spatial and anatomical action features, there is growing evidence that temporal features are also part of binding and retrieval processes. Starting from experiments on temporal stimulus-response compatibility (Grosjean & Mordkoff, 2001; Kunde, 2003; Kunde & Stöcker, 2002), that provide initial evidence for the integration of temporal features into action plans (Hommel, 2009), more recent studies directly demonstrated binding and retrieval of temporal features. Partial repetition costs as indicator for binding and retrieval processes have been demonstrated for temporal stimulus features (Bogon et al., 2017; Köllnberger et al., 2022) and temporal action features (Mocke et al., 2022).

What has been neglected in research on the integration of durations in action plans, is whether such features are restricted to categorical features that guide decisions between different responses, or whether binding and retrieval also applies to continuous properties of actual motor performance. The examples mentioned at the beginning show that the possible precision levels can range from a categorical, relative coding of duration (the longer/shorter of two durations) to a specific, continuous duration representation on a metric scale of (milli)seconds. Empirical findings and theoretical considerations suggest that the different stages of action planning and execution require different specification levels of action features (Glover, 2004; Prablanc & Pélisson, 1990;

Thomaschke et al., 2012a, 2012b; Wurm & Lingnau, 2015). Most actions are not entirely ballistic, i.e., some parameters of the action have to be adapted to a dynamic environment. Categorical features, such as effector identity, can already be integrated into an action plan before the action is initiated as an explicit representation. However, for metric action features, such as the specific spatial or temporal parameters of a movement, full integration into an action plan seems impractical because they usually require adaptive responses during action monitoring. Accordingly, action planning is supposed to involve predominantly categorical feature representations, whereas online control of the movement after initiation of the action involves specific metric features (Glover & Dixon, 2002; Thomaschke et al., 2012a, 2012b). When planning an action, a rough categorical specification of a temporal action feature (e.g., long) could thus first be integrated into the action plan, and its more precise specification (e.g., a specific duration) would then be performed automatically by sensorimotor loops based on the ongoing situation (Heuer, 1981). These considerations suggest that integration of response durations in action plans is based on categorical duration representations.

However, enacting a certain movement might still feed into action plans that were used to arrive at a categorical action decision. This would suggest that binding and retrieval accounts extend to action control proper. Investigating this question requires measures that capture continuous-metric properties of an action, rather than analyzing partial repetition costs for categorical stimulus and response features. A particularly potent measure in case of temporal features can be derived from the actual response durations of two successive stimulus-response episodes. If continuous information is integrated into action plans, the repetition of the stimulus should retrieve the continuous action duration of the previous response, thus increasing the similarity of the successive response durations as compared to situations with changing stimuli. Tentative evidence indeed points into this direction (Pfister et al., 2022; Varga et al., 2022). Repeating a stimulus across trials yielded more similar response durations as compared to a situation with stimulus changes across trials. However, the response duration effects observed in these studies were small, especially when compared to the effect sizes for response times and error rates commonly reported in the literature on binding and retrieval for categorical features. Several factors might be responsible for this state of affairs, including technical reasons related to the limited variability of action durations in typical short key press responses and mechanistic reasons related to the question of whether binding and retrieval are sensitive to actual metric parameters of executed actions. One way to assess the contribution of these factors is to implement an experimental setup that requires participants to respond to stimuli with action durations of different categorical lengths while still recording the actual, metric duration of each response. The present experiments implemented precisely this strategy.

To investigate the level of precision at which the integration and retrieval process of action durations operates, we used a prime-probe paradigm (Figure 1; cf., Hommel, 1998) wherein participants responded to visual prime and probe stimuli with short or long key presses. Two letters served as response cues for the prime response and indicated a short or long key press. This key press had to be executed as soon as the prime stimulus appeared and regardless of the features of the prime stimulus (blue and red triangles and circles). The probe response was a speeded short or long key press that was indicated by the shape of the probe stimulus (e.g., circle → long key press, triangle → short key press). As a first step, we conducted traditional binding analyses, which inform about binding and retrieval of categorical representations of response durations. Therefore, response times (RTs) and error rates (ERs) were analysed to determine partial repetition costs. We expected better performance in terms of lower RTs and ERs when both stimulus shape and response duration category repeated or switched from prime to probe, compared to partial repetitions that involve repeating one feature while switching the other. Crucially, the main goal of this study was to determine if the precision level of integrated response duration in action plans goes beyond a categorical level. Therefore, the main analysis focused on the similarity of actual response durations of the prime response and the probe response. If, in addition to the duration category, the metric response duration is bound and later retrieved by a repeated stimulus, two successive responses of the same category (short/long) should be more similar for shape repetitions than for shape switches.

In order to investigate this issue, we calculated the absolute difference of the response duration of the prime response and the response duration of the probe response ($|\Delta RD| = |RD_{\text{prime response}} - RD_{\text{probe response}}|$) for all response repetition trials. The smaller this value, the more similar are the sequential response durations. If continuous temporal information is integrated and retrieved by stimulus repetitions afterwards, $|\Delta RD|$-values should be smaller for shape repetitions than for shape switches.

Experiment 1

Material and Methods

Participants

We recruited 25 students from the University of Regensburg who participated for course credit or financial compensation to achieve an effective sample size of at least 20 participants after participant exclusion. This sample size ensured a power of $1 - \beta > .90$ for detecting an effect size of Cohen's $f > 0.4$ for partial repetition costs (interaction of Shape Sequence and RD Sequence) in RTs and ERs (GPower 3.1.9.2; Faul et al., 2007) assuming a correlation of at least $r = .5$ between the levels of the factors Shape Sequence and Response Duration (conservatively estimated based on data from Bogon et al., 2017). Data of two participants were excluded due to problems with timing of short responses, i.e., the rate of trials with inaccurate short response durations (≥ 120 ms and ≤ 150 ms) was more than three interquartile ranges above the third quartile of the sample distribution. Data of one further participant were excluded because of an extreme number of response cue errors (rate of responses during response cue presentation was more than three interquartile ranges above the third quartile of the sample distribution). The final sample consisted of 22 participants (age *M* = 22.8 years, *SD* = 2.8; 16 self-identified as female, 6 as male; 1 left-handed).

Apparatus and stimuli

Participants were sitting in a dimly lit room facing a 17" computer screen at a viewing distance of approximately 60 cm. They responded by pressing the spacebar of a standard QWERTZ keyboard by performing either short key presses (“dit” response: less than 120 ms distance between press and release of the key; cf., Kunde & Stöcker, 2002) or long key presses (“dah” response: distance between press and release of the key between 150 and 400 ms; cf., Kunde & Stöcker, 2002). Participants were instructed to execute the key presses with the right index finger and to leave the right index finger on the space bar throughout the whole experiment. The experiment was run in E-Prime (Version 2.0, Psychology Software Tools, Sharpsburg, USA). Prime and probe stimuli were four colored shapes made up of two different colors, blue (RGB: 0,112,192) and red (RGB: 192,0,0) and two different shapes, a circle (*D* = 4.5 cm) and an equilateral triangle (*h* = 4.5 and a = b = c = 5.2 cm) presented centrally on a grey screen (RGB: 192,192,192). Two black letters, “k” for “kurz” (German for “short”) and “l” for “lang” (German for “long”), served as response cue for the prime response.

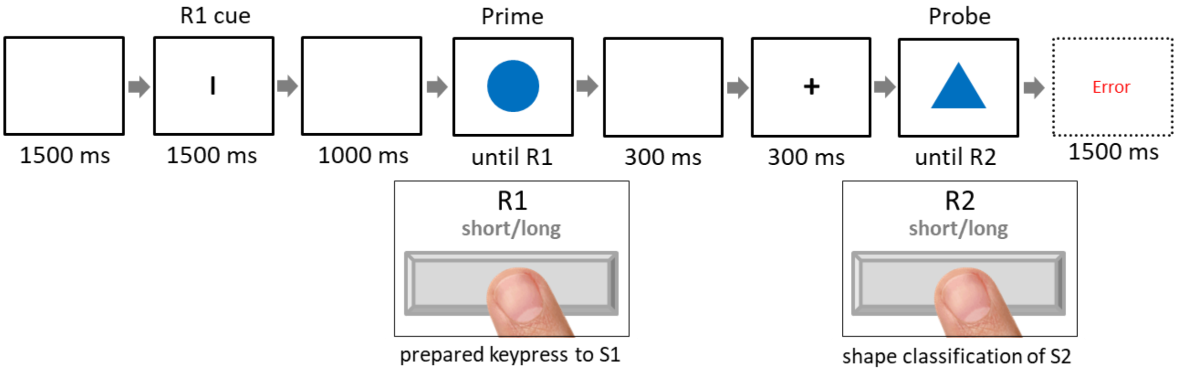

Figure 1. Trial sequence of the prime-probe paradigm adopted in Experiment 1. A response cue (one of two letters) for the prime response (R1) indicated a long or short key press. This key press had to be executed as soon as the prime stimulus appeared. The probe response (R2) was a short or long key press that was indicated by the shape of the probe stimulus. This design therefore allows orthogonally varying stimulus relation and response relation from prime to probe (response repetitions can be combined with stimulus repetitions but also with stimulus alternations).

Procedure

We applied a prime-probe paradigm in which participants had to execute two reponses per trial (Hommel, 1998). The first response was a short or long key press that was prepared according to the cue letter. This response had to be executed as soon as the prime stimulus appeared, independent of the shape or the color of the prime stimulus. The second response was a binary choice reaction to the shape of the probe stimulus.

Figure 1 shows an exemplary trial sequence. Each trial started with a blank of 1500 ms (inter-trial interval). Then, the response cue was presented for 1500 ms. The cued response, R1, had to be executed as soon as the prime stimulus appeared. The prime stimulus was visible until R1 was given (release of the space bar). After a blank of 300 ms and a fixation cross of 300 ms, the probe stimulus appeared. R2 had to be executed in response to the shape of the probe stimulus. The probe stimulus was visible until R2 was given (release of the space bar). When participants responded erroneous, an error message appeared for 1500 ms ("Error"). When a correct long key press lasted longer than 400 ms, participants received the feedback "long key press was too long". When participants did not respond within 3000 ms, they received the feedback "too slow". The experiment consisted of two practice blocks of 20 and 16 trials and three experimental blocks of 64 trials. The first practice block contained only the binary choice part of the trial sequence (probe stimulus and R2), the second practice block then included the complete trial sequence. The order of trials was randomized. Participants were instructed to respond as fast and accurately as possible. Half of the participants had to answer to the triangle with the long response and to the circle with the short response, for the other half of participants it was vice versa.

Design

For the analysis of RTs and ERs to test for partial repetition costs we used a 2 x 2 design with the within-subject factors Shape Sequence (repetition vs. switch) and Response Duration Sequence (RD Sequence; repetition vs. switch). RTs and ERs of R2 for all trials with correct R1 served as the dependent variables of interest.

For the analysis of response duration similarity between prime and probe (|ΔRD|) to determine the precision level of integrated response duration we used a 2 x 2 design with the within-subject factors Shape Sequence (repetition vs. switch) and Response Duration Category (RD Category; short vs. long). Here, the absolute difference in response durations of R1 and R2, calculated as $|\Delta RD| = |RD_{\text{prime response}} - RD_{\text{probe response}}|$, for all correct response repetition trials served as dependent variable of interest.

As the task-irrelevant color of the stimulus was irrelevant for answering our research question and had no effect on any of the dependent variables, we collapsed the data across the color feature. The results of analyses including Color Sequence (repetition vs. switch) as an additional factor for each dependent variable can be found in the Supplementary Material (Tables S1-S8).

Transparency and openness

We report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study, and we follow current Journal Article Reporting Standards (JARS; Kazak, 2018). All data and analysis code are available at https://osf.io/nsd4z/. Data were analyzed using R, version 4.2.2 (R Core Team, 2022), the *tidyverse* package bundle, version 1.3.2 (Wickham et al., 2019), the package *ez,* version 4.4-0 (Lawrence, 2016), and the package *effectsize*, version 0.8.2 (Ben-Shachar et al., 2020). This study's design and its analysis were not pre-registered. Data was collected in 2019 (Experiment 1) and 2020 (Experiment 2).

Results

Preprocessing

Raw data and analysis scripts are available on the Open Science Framework (https://osf.io/nsd4z/). Practice blocks and the first trial of each experimental block were excluded from analysis. Before analysing probe RTs and ERs, we excluded trials with response durations between 120 ms and 150 ms (4.0%) because these durations did not map on either of the two instructed categories. Furthermore, we excluded all trials with response cue errors (participants responded directly at the presentation of the response cue or within the first 100 ms of the prime presentation; 1.3%), erroneous responses to the prime (1.5%) and trials with response durations higher than 400 ms (3.5%). For RT analyses, we additionally excluded trials with erroneous responses to the probe (4.4%) and trials with RTs deviating more than three *SDs* from the individual condition mean (0.7%). Due to these constraints, 88.2% of all experimental trials were included for error analysis and 83.7% of all experimental trials were included for RT analysis. For the analysis of |ΔRD|, we considered only trials that were included in the RT analysis and additionally excluded trials with |ΔRD|-values deviating more than three *SDs* from the individual condition mean (0.5%).

Analyses of RTs and ERs

Figure 2 shows mean RTs and ERs as a function of Shape Sequence and RD Sequence (see Table 1 for full descriptive statistics). We conducted separate 2 (Shape Sequence : repetition vs. switch) x 2 (RD Sequence: repetition vs. switch) ANOVAs with repeated measures on all factors for each dependent variable.

For RTs, this analysis revealed a significant main effect of Shape Sequence, $F(1, 21) = 10.82$, $p = .003$, $\eta_p^2 = .34$, indicating generally higher RTs for shape switches compared to shape repetitions (502 ms vs. 481 ms). Moreover, we observed a significant interaction Shape Sequence x RD Sequence, $F(1, 21) = 58.76$, $p < .001$, $\eta_p^2 = .74$ (see Figure 2A). Participants responded slower when only the stimulus shape or the response duration switched, compared to when both features repeated or both switched. The main effect of RD Sequence was not significant, $F(1, 21) = 1.16$, $p = .294$, $\eta_p^2 = .05$.

For ERs, an analogous ANOVA also yielded a significant interaction Shape Sequence x RD Sequence, $F(1, 21) = 37.75$, $p < .001$, $\eta_p^2 = .64$ (see Figure 2B). Participants were more error prone, when only the stimulus shape or the response duration switched, compared to when both features repeated or both switched. None of the other effects was significant (all *F*s < 2.00).

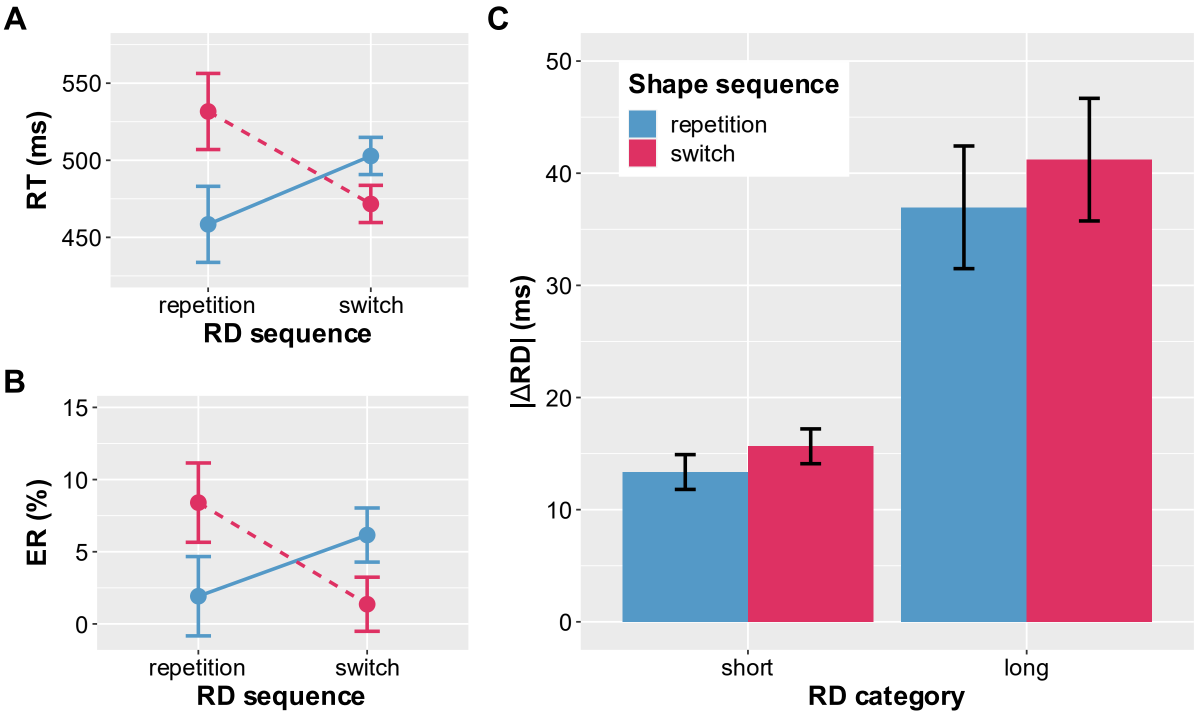

Figure 2. Main results of Experiment 1. Mean response times (RTs; Panel A) and error rates (ERs; Panel B) are shown as a function of response duration sequence (repetition vs. switch) and shape sequence (repetition vs. switch). Error bars in Panel A and B represent 95% confidence intervals of paired differences between shape repetitions and shape switches (Pfister & Janczyk, 2013) computed separately for response duration repetitions and response duration switches. Mean |ΔRD|-values for response duration repetitions (Panel C) are shown as a function of response duration category (short vs. long) and shape sequence (repetition vs. switch). Error bars in Panel C represent 95% confidence intervals of paired differences between shape repetitions and shape switches computed separately for short responses and long responses. In all panels, shape repetitions are indicated by blue color and shape switches by red color.

Analyses of response duration similarity (|ΔRD|)

In order to investigate the precision level of integrated response durations, we calculated the difference of the response duration of the prime response and the response duration of the probe response ($|\Delta RD| = |RD_{\text{prime response}} - RD_{\text{probe response}}|$) for all response repetition trials. Figure 2C plots these |ΔRD|-values for response repetitions as function of RD Category and Shape Sequence. The smaller the |ΔRD|-value, the more similar are the sequential response durations of the prime and probe responses. We then conducted a 2 x 2 ANOVA with the within factors Shape Sequence (repetition vs. switch) and RD Category (short vs. long) on the |ΔRD|-values. This revealed a significant main effect of RD Category, *F*(1, 21) = 121.93, $p < .001$, $\eta_p^2 = .85$, indicating generally smaller duration differences between sequential short responses than between sequential long responses (15 ms vs. 39 ms). Importantly, we observed a significant main effect of Shape Sequence, *F*(1, 21) = 6.29, $p = .020$, $\eta_p^2 = .23$, indicating that repeated responses came with more similar durations when the shape also repeated in comparison to repeated responses at shape switches. For short durations, the mean difference of |ΔRD|-values for shape repetitions and shape switches was 2.29 ms, 95% CI [0.74, 3.84], $d = 0.65$, 95% CI_d [0.19, 1.11]. For long durations, the mean difference of |ΔRD|-values for shape repetitions and shape switches was 4.25 ms, 95% CI [-1.22, 9.72], $d = 0.34$, 95% CI_d [-0.09, 0.77]. Although these effect estimations might suggest different standardized effect sizes for long and short responses, the Shape Sequence x Response Category interaction was not significant, *F*(1, 21) = 0.47, $p = .500$, $\eta_p^2 = .02$.

Discussion

In Experiment 1, analyses of RTs and ERs revealed partial repetition costs confirming binding of at least categorical response duration: Performance was better when stimulus shape and response duration category both repeated or switched from prime to probe relative to partial repetitions in which one factor repeated while the other switched. Most importantly, analyses of |ΔRD|-values revealed that for response category repetitions, the actual durations of the prime response and the probe response were more similar for shape repetitions than for shape switches. These results indicate that, additionally to the duration category, a more precise level of duration information is bound to the relevant shape feature and retrieved by this shape feature afterwards.

In Experiment 1, the stimulus in prime and probe consistently disappeared after the key was released. As a consequence, the presentation duration of the stimulus was defined by the response initiation time and the response duration. Thus, executing a long key press resulted in a long presentation duration and executing a short key press resulted in a short presentation duration. To rule out that the results in Experiment 1 were influenced by binding between stimulus presentation duration and stimulus shape, we conducted a second experiment in which we aimed to replicate the results of Experiment 1 with a stimulus duration that was independent of the response initiation and response duration. Furthermore, we increased the sample size to obtain more confident effect size estimations for |ΔRD|-differences between shape repetitions and shape switches in both response duration categories.

Experiment 2

Experiment 2 was a close replication of Experiment 1 that removed potential confounds due to the coupling of stimulus and response offset in the former experiment.

Material and Methods

Participants

We recruited 45 students from the University of Regensburg who participated for course credit or financial compensation to achieve an effective sample size of at least 40 participants after participant exclusion. This sample size ensured a power of $1 - \beta > .80$ for detecting an effect size of Cohen's $d > 0.40$ for |ΔRD|-differences between shape repetitions and shape switches (GPower 3.1.9.2; Faul et al., 2007). Data of three participants had to be excluded because their error rate at the prime stimulus was more than 1.5 interquartile ranges above the third quartile of the sample distribution. Data of two further participants were excluded due to problems with timing of the response durations, i.e., the rate of trials with inaccurate short or long response durations (≥ 120 ms and ≤ 150 ms) was more than 1.5 interquartile ranges above the third quartile of the sample distribution or above 30%. The final sample consisted of 40 participants (age *M* = 23.2 years, *SD* = 4.3; 34 self-identified as female, 6 as male; 4 left-handed).

Stimuli and procedure

The stimuli and the procedure of Experiment 2 mirrored that of Experiment 1, with the exception that the prime and probe stimuli were visible for 100 ms (rather than being displayed until key release), followed by a blank screen until response onset. Furthermore, in Experiment 2 a trial was terminated after an error was made at the response cue or at the prime.

Results

Preprocessing

Practice blocks and the first trial of each experimental block were excluded from analysis. As in Experiment 1, before analysis of RTs and ERs for the probe response, we excluded trials with response durations between 120 ms and 150 ms (8.2%), all trials with response cue errors (2.3%), erroneous responses to the prime (2.8%) and trials with response durations higher than 400 ms (2.8%). For RT analysis, we additionally excluded trials with erroneous responses to the probe (6.7%) and trials with RTs deviating more than three *SDs* from the individual condition mean (0.6%). In sum, due to these constraints, 82.6% of all experimental trials were included for error analysis and 76.7% of all experimental trials were included for RT analysis. For the analysis of $|\Delta RD|$, we considered only trials that were included in the analysis of reaction times and additionally excluded trials with $|\Delta RD|$ deviating more than three *SDs* from the individual condition mean (0.1%).

Analyses of RTs and ERs

Figure 3 shows mean RTs and ERs as a function of Shape Sequence and RD Sequence (see Table 2 for detailed descriptive statistics). Analyses were as for Experiment 1. The ANOVA on RTs yielded a significant main effect of Shape Sequence, $F(1, 39) = 4.34$, $p = .044$, $\eta_p^2 = .10$, indicating generally higher RTs at shape switches compared to shape repetitions (472 ms vs. 464 ms). We observed a significant interaction Shape Sequence x RD Sequence, $F(1, 39) = 52.36$, $p < .001$, $\eta_p^2 = .57$ (see Figure 3A). Participants responded slower when only the stimulus shape or the response duration switched, compared to when both features repeated or both switched. The main effect of RD Sequence was not significant, $F(1, 21) = 0.14$, $p = .711$, $\eta_p^2 = .004$. An analogous ANOVA for errors also yielded a significant interaction Shape Sequence x RD Sequence, $F(1, 39) = 39.73$, $p < .001$, $\eta_p^2 = .51$ (see Figure 3B). None of the other effects was significant (all *F*s < 1.58).

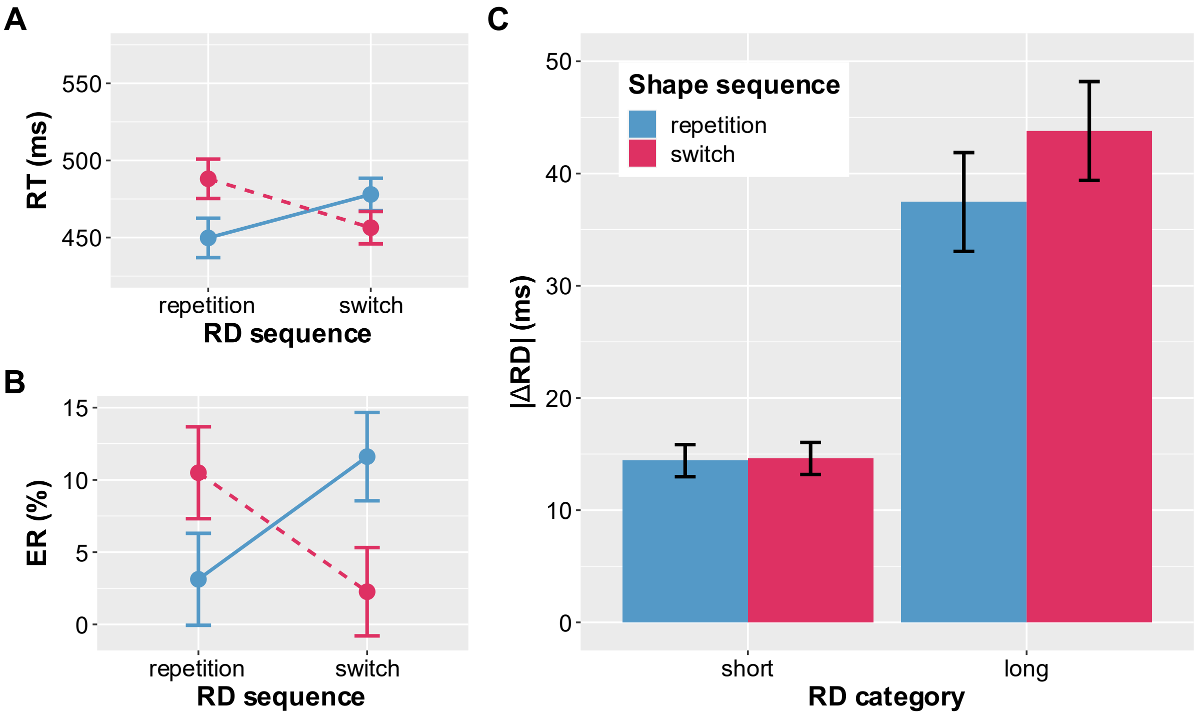

Figure 3. Main results of Experiment 2. Mean response times (RTs; Panel A) and error rates (ERs; Panel B) are shown as a function of response duration sequence (repetition vs. switch) and shape sequence (repetition vs. switch). Error bars in Panel A and B represent 95% confidence intervals of paired differences between shape repetitions and shape switches (Pfister & Janczyk, 2013) computed separately for response duration repetitions and response duration switches. Mean |ΔRD|-values for response duration repetitions (Panel C) are shown as a function of response duration category (short vs. long) and shape sequence (repetition vs. switch). Error bars in Panel C represent 95% confidence intervals of paired differences between shape repetitions and shape switches computed separately for short responses and long responses. In all panels, shape repetitions are indicated by blue color and shape switches by red color.

Analyses of response duration similarity (|ΔRD|)

Figure 3C plots |ΔRD|-values for response repetitions as function of RD Category and Shape Sequence. The smaller the |ΔRD|-value, the more similar are the sequential response durations of the prime and probe responses. A 2 x 2 ANOVA with the within factors Shape Sequence (repetition vs. switch) and RD Category (short vs. long) on the |ΔRD|-values revealed a significant main effect of RD Category, $F(1, 39) = 309.08$, $p < .001$, $\eta_p^2 = .89$, indicating generally smaller duration differences between sequential short responses than between sequential long responses (15 ms vs. 41 ms).

Crucually, we observed a significant main effect Shape Sequence, $F(1, 39) = 10.41$, $p = .003$, $\eta_p^2 = .21$, indicating that durations of repeated responses were more similar, when the shape also repeated in comparison to durations of repeated responses at shape switches. In Experiment 2, the Shape Sequence x RD Category interaction was also significant, $F(1, 39) = 5.89$, $p = .020$, $\eta_p^2 = .13$. For short durations, $|\Delta RD|$-values for shape repetitions did not differ significantly from $|\Delta RD|$-values for shape switches, $t(39) = 0.27$, $p = .786$, $\Delta = 0.19$ ms, 95% CI = [-1.24 ms, 1.62 ms], $d = 0.04$, 95% CI_d = [-0.27, 0.35]. For long durations, this comparison was significant, $t(39) = 2.91$, $p = .006$, with a mean difference between $|\Delta RD|$-values for shape repetitions and shape switches of 6.3 ms, 95% CI = [1.92 ms, 10.73 ms], $d = 0.46$, 95% CI_d = [0.13, 0.78].

Discussion

In Experiment 2, analyses of RTs and ERs replicated binding effects for categorical response duration in terms of partial repetition costs. Crucially, we again found evidence that a more precise level of duration information is bound to the shape feature and can be retrieved afterwards: Analyses of $|\Delta RD|$-values revealed that for response repetitions, the actual durations of the prime response and the probe response were more similar for shape repetitions than for shape switches. Unlike in Experiment 1, this effect was evident only for long key presses.

Pooled Analyses

Lastly, we performed an analysis of the pooled data from both experiments to obtain a reliable estimate of the effect size for the integration of metric response duration. A 2 (Shape Sequence: repetition vs. switch) x 2 (RD Category: short vs. long) - ANOVA on the $|\Delta RD|$-values revealed a significant main effect of RD Category, $F(1, 61) = 428.95$, $p < .001$, $\eta_p^2 = .88$, indicating generally smaller duration differences between sequential short responses than between sequential long responses (15 ms vs. 40 ms). Most importantly, this revealed a significant main effect Shape Sequence, $F(1, 61) = 16.94$, $p < .001$, $\eta_p^2 = .22$, and a significant Shape Sequence x RD Category interaction, $F(1, 61) = 5.85$, $p = .019$, $\eta_p^2 = .09$: Durations of sequential responses were more similar, when the shape also repeated in comparison to durations of sequential responses at shape switches and this effect was more pronounced for long durations than for short durations. For short durations, |ΔRD|-values for shape repetitions did not differ significantly from |ΔRD|-values for shape switches, $t(61) = 1.74$, $p = .087$, $\Delta = 0.94$ ms , 95% CI = [-0.14 ms, 2.02 ms], $d = 0.22$, 95% CI_d = [-0.03, 0.48]. For long durations, this comparison was significant, $t(61) = 3.33$, $p < .001$, with a mean difference between|ΔRD|-values for shape repetitions and shape switches of $\Delta = 5.59$ ms , 95% CI = [2.24 ms, 8.95 ms], $d = 0.42$, 95% CI_d = [0.16, 0.69].

General Discussion

The aim of this study was to determine whether the integration of action duration is based exclusively on categorical duration representations or also on continuous metric representations. In a prime-probe paradigm, participants responded to visual stimuli with short or long key presses. In a first step, analyses of RTs and ERs in both experiments revealed partial repetition costs, confirming binding and retrieval of at least categorical representations of response durations: Performance was better when the stimulus shape and response duration category both repeated or alternated from prime to probe, compared with partial repetitions in which one feature repeated while the other alternated. Most importantly, analyses of |ΔRD|-values suggest that the representational level of bound duration goes beyond a categorical representation: Two consecutive responses of the same category (short/long) were more similar when the shape was also repeated than when it was alternated. This points to the conclusion that continuous temporal information is integrated into an action plan and subsequently retrieved by stimulus repetition.

Overall, our results imply that action duration is integrated into the action plan in a relatively precise form already during action planning. This is remarkable in that it is assumed that features are first integrated into an action plan at a crude categorical level, which is then specified by subsequent sensorimotor processes during action execution based on situational conditions (Glover & Dixon, 2002; Heuer, 1981; Thomaschke et al., 2012a, 2012b). Thus, rather than precising the integrated categorical duration representation, situational adaptation seems to be an update of the already precise integrated duration. But how can we imagine the interplay of discrete and continuous features in an action plan? It appears plausible that a specific duration is achieved by activating certain categorical codes (e.g., “long” vs. “short”) more strongly than others (cf., Hommel, 2019; Hommel et al., 2001). Crucially, our results show that the result of this combined activation, i.e., the continuous duration of the action, is bound to and retrieved by stimuli that accompany an action.

Importantly, for answering the question of whether binding and retrieval are sensitive to actual metric parameters of executed actions, the task relevance of the bound features is not of primary importance. Nevertheless, in order to get a complete picture of our findings and conclusions, it is still worthwhile to deconstruct the binding and retrieval scenarios of our study in terms of the task relevance of the features involved. We implemented an experimental setup that required participants to respond to successive stimuli of the same or different shape with action durations of the same or different categorical length. To achieve this setting, we used a prime-probe paradigm with two stimulus-response episodes per trial. During the prime episode, the stimulus was merely a go signal for performing a short or long response indicated by a preceding cue. During the probe episode, the stimulus was task relevant in that participants had to classify its shape by a long or a short key press. Our results suggest that the duration of the prime response is bound to the shape of the prime and subsequently retrieved if the probe stimulus has the same shape as the prime stimulus. Therefore, our conclusions were derived from a setting in which the duration of the response was task relevant during binding (prime) and retrieval (probe), whereas the involved stimulus shape was task irrelevant during binding, but task relevant in the retrieval scenario. However, the integration of metric response features does not appear to be restricted to relevant response features. Our results complement subtle evidence for the integration of metric response features derived from experiments in which response duration was irrelevant to the task (Pfister et al., 2022; Varga et al., 2022).

Having reflected the task relevance of the features involved in our experimental setting, one might be inclined to consider an alternative explanation for our findings. Assuming that, strictly speaking, the prime in shape-switch trials represents an "incompatible" stimulus-response scenario, our findings could also be consistent with a categorical integration model and motor errors towards the compatible response duration (cf. Grosjean & Mordkoff, 2001). In the applied paradigm, the shape of the prime stimulus merely served as a go signal for the previously cued response and was therefore task irrelevant. However, because shape was task relevant in the probe, participants were trained to produce a specific response duration to a specific shape. Therefore, in shape switch trials, participants had to respond with the "incompatible" response duration to the shape of the prime stimulus. Thus, it is also conceivable that the duration was integrated at a categorical level during the prime and that this categorical duration is later retrieved in the probe. However, in "incompatible" primes, the executed duration of the prime response may have been adjusted towards the compatible duration without updating the integrated duration. That means, in case of an "incompatible" short response, participants may have pressed longer, and in case of an "incompatible" long response, participants may have pressed shorter than the duration that was specified in the action plan. This would also have resulted in lower similarity of two consecutive responses of the same category (short/long), i.e., higher $|\Delta RD|$-values, when the shape alternated than when it was repeated. In our analyses, the measure of interest was the absolute difference between the duration of the prime response and the duration of the probe response ($|\Delta RD| = |RD_{\text{prime response}} - RD_{\text{probe response}}|$) in response repetition trials. To evaluate this alternative explanation more directly, we additionally calculated and analyzed post hoc the relative differences between successive durations for response repetition trials ($\Delta RD = RD_{\text{prime response}} - RD_{\text{probe response}}$). Table 1 summarizes the results of these analyses. For repeated short response durations from prime to probe, mean ΔRD-values were positive for both shape switch and shape repetition trials, indicating that the duration of the prime response was longer than the duration of the probe response for both trial types. Furthermore, this positive difference was more pronounced for shape-switch trials. For repeated long response durations from prime to probe it was vice versa: mean ΔRD-values were negative for both shape-switch and shape-repetition trials, indicating that the duration of the prime response was shorter than the duration of the probe response for both trial types. Again, this negative difference was more pronounced for shape switch trials. At a first glance, these results are indeed compatible with a model involving integration and retrieval of categorical response duration and non-integrated motor errors towards the “compatible” response duration in the prime. On the other hand, for a number of reasons, the results of our study can still be more plausibly explained by the integration of continuous response durations into action plans. First, with regard to the results of the analyses of relative ΔRD-values (see Table 1), it should be taken into account that even for shape-repetition trials, the probe response deviated positively from the probe response for short response durations and deviated negatively for long response durations. This is consistent with the observation from a temporal stimulus-response compatibility experiment that there is a tendency for short response durations to be overshot and long response durations to be undershot irrespective of stimulus-response-compatibility (Grosjean & Mordkoff, 2001). With this in mind, if the previously integrated continuous duration is not retrieved due to a shape switch from prime to probe, it is rather logical that the new duration to be defined for the probe response tends to deviate in the specific direction, i.e., it is undershot for long response durations and overshot for short response durations. Second, temporal stimulus-response compatibility effects are primarily characterized by delayed responses to incompatible stimulus-response combinations (Grosjean & Mordkoff, 2001; Kunde, 2003; Kunde & Stöcker, 2002). In the present experiment, prime responses to „incompatible“ prime stimuli were not initiated slower than prime responses to „compatible“ prime stimuli[1]. This implies that the “incompatibility” of the prime did not cross the perceptual threshold to affect the duration of the prime response. Third, first tentative evidence for the integration of continuous response duration was obtained without involving any putative stimulus-response compatibilities (Pfister et al., 2022). In an experimental setting where two stimuli (D and F / J and K) were mapped to

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[1] We compared RTs of the prime response for “incompatible” and “compatible” primes in the pooled data of both experiments. This did not reveal a significant effect of compatibility on prime RTs, *t*(61) = 1.34, *p* = .184, Δ = 6.21 ms , 95% CI = [-3.04 ms, 15.46 ms], *d* = 0.17, 95% CI_d = [-0.08, 0.42].

one response key (left/right), the duration of successive responses on the same key also tended to be more similar when accompanied by stimulus repetitions compared to stimulus switches. In summary, these considerations support an interpretation of our findings that involves the integration of continuous response durations into action plans.

But what exactly determines response durations for a given action episode? One major factor likely is response monitoring, as agents will only terminate ongoing behavior if they can be sufficiently sure to have performed the intended action (e.g., Horvath et al., 2018). This factor raises a potential alternative explanation for the increased similarity of response durations in the face of stimulus repetitions. Like almost all cognitive processes, such monitoring likely fluctuates across time, e.g., regarding the amount of evidence required for participants to engage in terminating an ongoing action. Maybe, then, it is not the response duration itself that is bound and retrieved, but rather the evidence criterion or threshold for the monitoring process. There is indeed evidence that abstract control states can become bound to stimuli and retrieved later on (Dignath et al., 2019; Dignath et al., 2021; Foerster et al., 2022; Grant et al., 2022; Whitehead et al., 2020). This account of the present findings is reinforced by the possibility that a control state may be present already during response-related decision making and during action initiation, thus allowing for easier integration with concurrent stimulus features. The control state account would also be able to explain previous observations of binding and retrieval for response durations (Pfister et al., 2022; Varga et al., 2022). One way to disentangle control states from binding and retrieval of actual response durations would be to assess factors that have been observed to counter binding of control states while binding of actual response durations might still stay intact in such situations (Whitehead et al., 2021). An even more direct way would involve assessing the temporal evolution of individual force profiles of a key-press response as the control state account would not predict stimulus repetitions to increase similarity before reaching a certain threshold. Early signs of retrieval of a certain motor pattern would thus yield convincing evidence for the idea of binding and retrieval of metric temporal features.

The results of the |ΔRDur| analyses of the pooled data further revealed different magnitudes of binding effects for short and long key presses. This is supposedly because the categorical limits of possible durations (short: max. 120 ms; long: 150-400 ms) impose constraints on the variance of simple short key presses compared to long key presses. This provides per se a different range of possible effect sizes for long and short key presses. This reading of the data is in line with the observation of only binding and retrieval effects for metric response durations in previous work (Pfister et al., 2022; Varga et al., 2022). By integrating long response durations into the design of the present study, we were able to corroborate the vague evidence for these binding effects. The results therefore underscore the utility of assessing response durations as a unique approach to studying cognitive function (Pfister et al., 2023).

Constraints of Generality Statement

Feature binding and retrieval are a basic property of human perception and action (Frings et al., 2020), and alterations are associated with severe conditions such as schizophrenia (Hemsley, 2005). Because our results tackle a fundamental aspect of these processes, we expect them to generalize to most if not all healthy individuals, whereas they likely do not apply to states of significantly altered perceptual or motor cognition.

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Compliance with Ethical Standards

Disclosure of potential conflict of interest

All authors declare that they have no conflict of interest.

Research involving Human Participants and/or Animals

All procedures performed in studies involving human participants were in accordance with the ethical standards of the national research committee and with the 1964 Helsinki declaration and its later amendments.

Informed consent

Informed consent was obtained from all individual participants included in the study.

Table 1

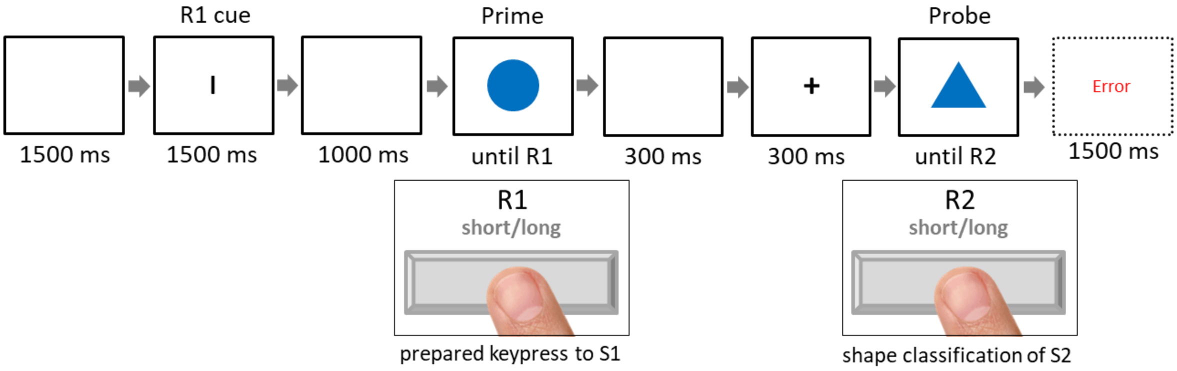
Descriptive Statistics and Analyses of relative ΔRD-values for Pooled Data of Both Experiments.

RD category	Shape repetition		Shape switch		*t*(61)	*p*	Cohen's *d*	95% CI
	M	*SD*	*M*	*SD*				
Short RD	1.73	7.22	3.35	6.80	2.18	0.033	0.28	[0.02, 0.53]
Long RD	-9.08	20.39	-14.55	21.46	-2.23	0.029	- 0.28	[-0.54, -0.03]

Note. Mean relative ΔRD-values for each RD category are shown for shape repetition trials and shape switch trials, as well as the results of *t*-tests comparing the ΔRD-values for these trial types within each RD category.

Figure 1

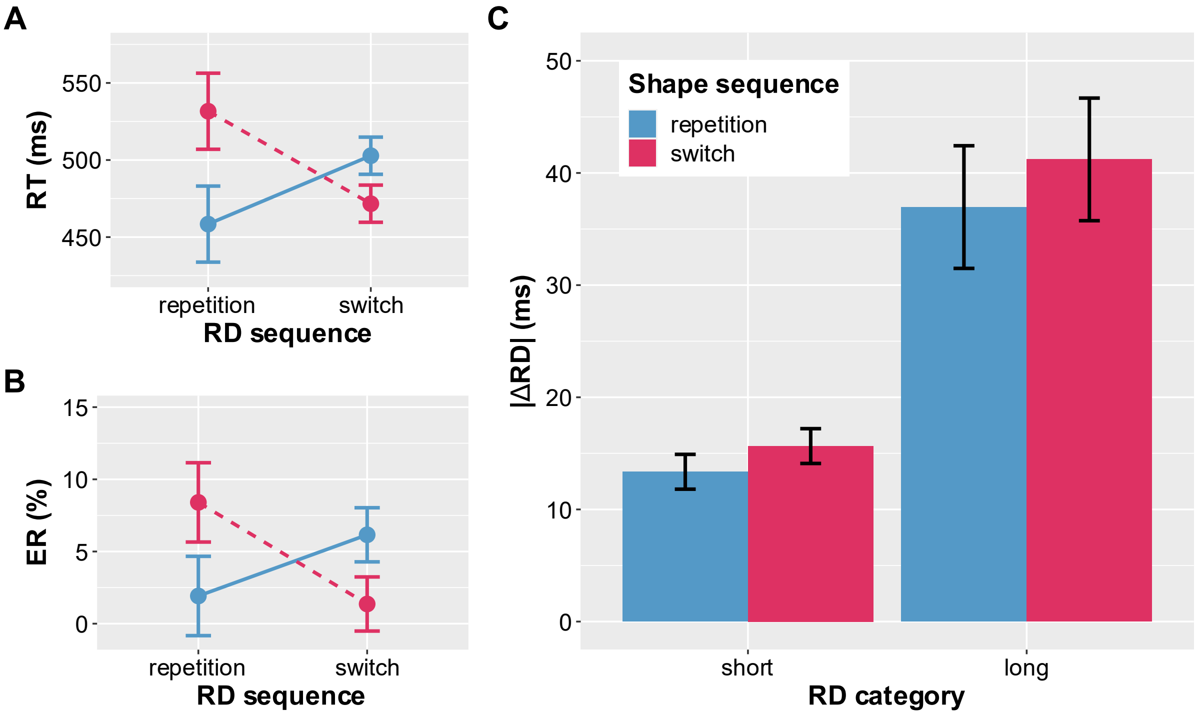
Trial Sequence of the Prime-Probe Paradigm adopted in Experiment 1.



Note. A response cue (one of two letters) for the prime response (R1) indicated a long or short key press. This key press had to be executed as soon as the prime stimulus appeared. The probe response (R2) was a short or long key press that was indicated by the shape of the probe stimulus. This design therefore allows orthogonally varying stimulus relation and response relation from prime to probe (response repetitions can be combined with stimulus repetitions but also with stimulus alternations).

Figure 2

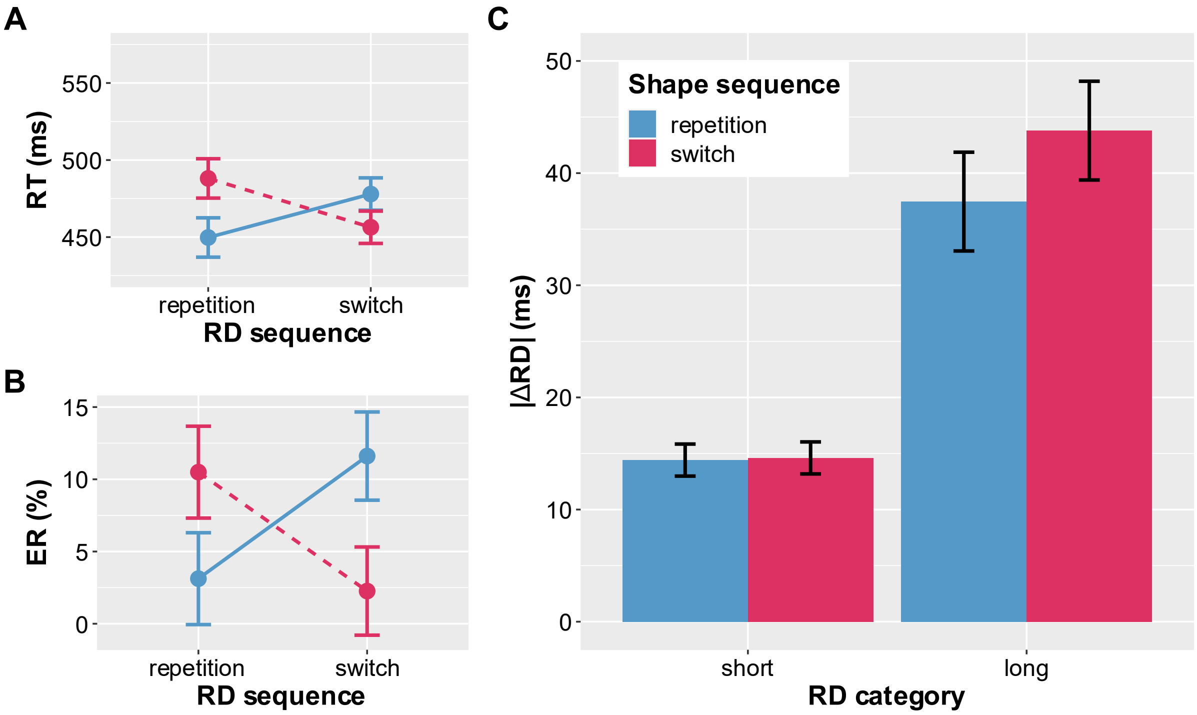
Main Results of Experiment 1.



Note. Mean response times (RTs; Panel A) and error rates (ERs; Panel B) are shown as a function of response duration sequence (repetition vs. switch) and shape sequence (repetition vs. switch). Error bars in Panel A and B represent 95% confidence intervals of paired differences between shape repetitions and shape switches (Pfister & Janczyk, 2013) computed separately for response duration repetitions and response duration switches. Mean |ΔRD|-values for response duration repetitions (Panel C) are shown as a function of response duration category (short vs. long) and shape sequence (repetition vs. switch). Error bars in Panel C represent 95% confidence intervals of paired differences between shape repetitions and shape switches computed separately for short responses and long responses. In all panels, shape repetitions are indicated by blue color and shape switches by red color.

Figure 3

Main Results of Experiment 2.



Note. Mean response times (RTs; Panel A) and error rates (ERs; Panel B) are shown as a function of response duration sequence (repetition vs. switch) and shape sequence (repetition vs. switch). Error bars in Panel A and B represent 95% confidence intervals of paired differences between shape repetitions and shape switches (Pfister & Janczyk, 2013) computed separately for response duration repetitions and response duration switches. Mean |ΔRD|-values for response duration repetitions (Panel C) are shown as a function of response duration category (short vs. long) and shape sequence (repetition vs. switch). Error bars in Panel C represent 95% confidence intervals of paired differences between shape repetitions and shape switches computed separately for short responses and long responses. In all panels, shape repetitions are indicated by blue color and shape switches by red color.

Supplementary Material

As the task-irrelevant color of the stimulus was irrelevant for answering our research question and had no effect on any of the dependent variables, we collapsed the data across the color feature for our analyses described in the main text. Here, we additionally provide the means and results of analyses including Color Sequence (repetition vs. switch) as an additional factor for each dependent variable.

Table S1

Mean RTs and ERs for Experiment 1.

		Shape Repetition		Shape Switch	
Measure		Color Repetition	Color Switch	Color Repetition	Color Switch
RT	RD Repetition	451.98	464.89	534.75	528.54
	RD Switch	499.24	506.34	469.72	473.60
ER	RD Repetition	2.41	1.43	8.51	8.30
	RD Switch	7.79	4.52	2.08	0.64

Note. Mean RTs (ms) and ERs (%) are displayed as a function of Shape Sequence (repetition vs. switch), Color Sequence (repetition vs. switch) and Response Duration Sequence (RD Sequence; repetition vs. switch).

Table S2

Results of the 2 x 2 x 2 ANOVA on RTs and ERs for Experiment 1.

Measure	Effect	df_n	df_d	F	p	η_p^2
RT	Shape Sequence (S)	1	21	10.82	.003	.34
	Color Sequence (C)	1	21	0.64	.435	.03
	RD Sequence (R)	1	21	1.16	.294	.05
	S x C	1	21	1.24	.278	.06
	S x R	1	21	58.76	< .001	.74
	C x R	1	21	0.05	.833	< .01
	S x C x R	1	21	0.83	.373	.04
ER	Shape Sequence (S)	1	21	1.64	.215	.07
	Color Sequence (C)	1	21	3.60	.072	.15
	RD Sequence (R)	1	21	2.00	.172	.09
	S x C	1	21	0.94	.344	.04
	S x R	1	21	37.75	< .001	.64
	C x R	1	21	1.44	.243	.06
	S x C x R	1	21	0.17	.683	.01

Note. The ANOVA examined RTs and ERs as a function of three within-subject factors Shape Sequence (repetition vs. switch), Color Sequence (repetition vs. switch) and Response Duration Sequence (RD Sequence; repetition vs. switch).

Table S3

Mean │ΔRD│-values for Experiment 1.

		Shape Repetition		Shape Switch	
Measure		Color Repetition	Color Switch	Color Repetition	Color Switch
│ΔRD│	Short RD	14.12	12.70	15.24	16.28
	Long RD	36.57	37.06	39.98	42.16

Note. Mean │ΔRD│-values are displayed as a function of Response Duration Category (short vs. long), Shape Sequence (repetition vs. switch) and Color Sequence (repetition vs. switch).

Table S4

Results of the 2 x 2 x 2 ANOVA on |ΔRD|-values for Experiment 1.

Measure	Effect	df_n	df_d	F	p	η_p^2
|ΔRD|	RD Category (R)	1	21	114.61	< .001	.85
	Shape Sequence (S)	1	21	6.39	.020	.23
	Color Sequence (C)	1	21	0.19	.669	.01
	R x S	1	21	0.44	.513	.02
	R x C	1	21	0.84	.371	.04
	S x C	1	21	0.9	.355	.04
	R x S x C	1	21	0.04	.843	< .01

Note. The ANOVA examined |ΔRD|-values as a function of three within-subject factors Response Duration Category (short vs. long), Shape Sequence (repetition vs. switch) and Color Sequence (repetition vs. switch).

Table S5

Mean RTs and ERs for Experiment 2.

		Shape Repetition		Shape Switch	
Measure		Color Repetition	Color Switch	Color Repetition	Color Switch
RT	RD Repetition	447.05	452.42	485.96	490.19
	RD Switch	473.32	482.56	458.50	454.27
ER	RD Repetition	3.18	3.07	11.89	9.10
	RD Switch	10.90	12.31	2.15	2.37

Note. Mean RTs (ms) and ERs (%) are displayed as a function of Shape Sequence (repetition vs. switch), Color Sequence (repetition vs. switch) and Response Duration Sequence (RD Sequence; repetition vs. switch).

Table S6

Results of the 2 x 2 x 2 ANOVA on RTs and ERs for Experiment 2.

Measure	Effect	df_n	df_d	*F*	*p*	η_p^2
RT	Shape Sequence (S)	1	39	4.34	.044	.1
	Color Sequence (C)	1	39	1.58	.216	.04
	RD Sequence (R)	1	39	0.14	.711	< .01
	S x C	1	39	2.16	.149	.05
	S x R	1	39	52.36	< .001	.57
	C x R	1	39	0.15	.697	< .01
	S x C x R	1	39	0.9	.349	.02
ER	Shape Sequence (S)	1	39	1.58	.216	.04
	Color Sequence (C)	1	39	0.25	.623	.01
	RD Sequence (R)	1	39	0.02	.903	< .01
	S x C	1	39	1.87	.180	.05
	S x R	1	39	39.73	< .001	.51
	C x R	1	39	3.07	.087	.07
	S x C x R	1	39	0.27	.606	.01

Note. The ANOVA examined RTs and ERs as a function of three within-subject factors Shape Sequence (repetition vs. switch), Color Sequence (repetition vs. switch) and Response Duration Sequence (RD Sequence; repetition vs. switch).

Table S7

Mean |ΔRD|-values for Experiment 2.

		Shape Repetition		Shape Switch	
Measure		Color Repetition	Color Switch	Color Repetition	Color Switch
|ΔRD|	Short RD	14.39	14.31	13.52	15.58
	Long RD	38.25	36.46	43.57	44.03

Note. Mean |ΔRD|-values are displayed as a function of Response Duration Category (short vs. long), Shape Sequence (repetition vs. switch) and Color Sequence (repetition vs. switch).

Table S8

Results of the 2 x 2 x 2 ANOVA on |ΔRD|-values for Experiment 1.

Measure	Effect	df_n	df_d	F	p	η_p^2
|ΔRD|	RD Category (R)	1	39	318.48	< .001	.89
	Shape Sequence (S)	1	39	10.36	.003	.21
	Color Sequence (C)	1	39	0.03	.857	< .01
	R x S	1	39	5.99	.019	.13
	R x C	1	39	1.15	.291	.03
	S x C	1	39	1.62	.21	.04
	R x S x C	1	39	0	.972	< .01

Note. The ANOVA examined |ΔRD|-values as a function of three within-subject factors Response Duration Category (short vs. long), Shape Sequence (repetition vs. switch) and Color Sequence (repetition vs. switch).