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Motor plans persist to influence subsequent actions with four or more response alternatives

Valeria Tretyak & Kielan Yarrow^{*}

Department of Psychology,
City University London

^{*} Author for correspondence:

Kielan Yarrow,
Social Science Building,
City University,
Northampton Square,
London EC1V 0HB

Tel: +44 (0)20 7040 8530
Fax: +44 (0)20 7040 8580
Email: kielan.yarrow.1@city.ac.uk

Abstract

Motor activity has the potential to persist after action and influence subsequent behaviour. A standard approach to isolating a motoric influence is to map two stimuli onto each response, so that response and stimulus repetition can be dissociated. A response-only response-repetition (RoRR) effect can then be assessed, arising if the same response made to two unrelated stimuli is nonetheless produced more rapidly. This kind of motoric behavioural influence of one response on the next has proved elusive in reaction time tasks involving choices between key presses, at least when stimuli mapped to each response are difficult to categorise together. However, such tasks have traditionally involved only a few response alternatives. We hypothesised that a larger load on the motor system might prevent participants from holding all possible action plans active throughout an experiment, and thus reveal trial-to-trial motor priming in the form of an RoRR effect. In our first experiment, increasing the number of response alternatives to four or eight yielded a reliable RoRR effect. This effect was replicated in Experiment 2, where it also proved persistent across practice and resistant to changes in response configuration. Our results are consistent with evidence of motoric perseveration in other kinds of motor task, such as reaching and grasping, and have implications for the generation of speeded decisions in a range of activities.

Keywords: Reaction times, choice RT, response repetition, information reduction paradigm, motor system

Introduction

A classic finding in experimental psychology is that reaction time (RT) in choice tasks depends in a systematic fashion upon the previous frequencies of the different stimulus categories in the experiment (Luce, 1986). Moreover, even if the overall frequencies with which different stimuli appear are well matched, reaction time on trial N is affected by the precise pattern of stimuli experienced in immediately preceding trials (Bertelson, 1961; Hyman, 1953). Early reports highlighted the response-repetition (RR) effect. In the now well-developed language of sequential effects, this is a first-order sequential effect, where a repeated response is quicker than an alternation. First-order repetition costs (or, equivalently, alternation benefits) have also been observed, but these are less common (Kirby, 1972), particularly when more than two responses are available (Soetens, Boer & Hueting, 1985), and generally arise only with longer response-stimulus intervals (RSIs). Many authors have also examined the higher-order influences of trials N-2, N-3 etc. on the current trial. However, effects from further back in the stimulus history appear much reduced with more than two responses (Gökaydin, Ma-Wyatt, Navarro, & Perfors, 2011). Here we are concerned primarily with the classic first-order effect, which simplifies our presentation.

The cognitive locus of the response repetition effect

Early work on the response-repetition effect attempted to localise it within a putative serial information-processing pathway which progresses from sensory analysis, to response selection, to response preparation and execution. In a typical choice RT task, if RT on trial N is quicker when trial N-1 contained the same stimulus, this might reflect a speed-up in processing at any or all information-processing loci. To expand, we might be quicker to perceive a repeated stimulus, or quicker to translate its meaning into a response, or quicker to refresh a motor plan to send to the

muscles of the body. The early literature introduced two approaches to distinguish these possibilities.

Firstly, several authors utilised the additive-factors method (Sternberg, 1969, 2001), which is a development of Donders' (1868) chronometric logic. When two known RT effects are combined factorially in a single experiment, an interaction between them suggests that they arise from a common processing stage. Following this approach, the RR effect has been shown to interact with stimulus-response compatibility (Bertelson, 1963; Kornblum, 1969; Soetens, Boer & Hueting, 1985) and with the number of response alternatives (Biederman & Stacy, 1974; Hyman, 1953; Kornblum, 1975). It does not interact with visual stimulus quality (Hansen and Well, 1984). Most recently, Adam & Koch (2009) have demonstrated an interaction between the RR effect and the benefit provided by partial advanced cuing of the upcoming target/response in a four-choice task. Collectively, these results seem most consistent with an RR locus at the response selection (i.e. decision-making) stage (but see Rabbitt and Vyas, 1973, for exceptions).

A second approach to identifying the locus of the RR benefit, known as the information-reduction procedure, was introduced by Bertelson (1965) and involves mapping more than one stimulus onto each possible response. This allows one to differentiate between the effects of stimulus repetition and response repetition, because a response repetition can now occur without a stimulus repetition. Bertelson (1965) mapped two even digits onto one response and two odd digits onto another response. This allowed for three possible first-order relationships, labelled "identity" (stimulus and response repetition), "equivalence" (stimulus changes, response repeats) and "difference" (stimulus and response both change). Bertelson found that participants were significantly faster on equivalence trials than on difference trials, speeding up almost to the same extent as they did in identity trials. Hereafter, we refer to RT improvements that occur when stimuli change but responses remain the same as *response-only* response-repetition (RoRR) effects. At first glance, it appears that RoRR effects can only have a motoric locus, because neither the stimulus nor the stimulus-response mapping has been repeated. They might therefore result from persistent

activation in the motor system providing a head start to the subsequent response (or else perhaps some biomechanical advantage).

Bertelson's result did not, however, go unchallenged for long. Rabbitt (1968) found a much less dramatic RoRR effect prior to substantial practice, using lower versus higher-value digits as stimuli. Smith (1968) not only failed to find an RoRR benefit with a long RSI and complex stimuli (a red "1" or green "2" for one response, and vice versa for the other), she actually obtained a cost. More recently, Pashler and Baylis (1991) suggested that these contrasting results might crucially reflect the degree to which the two stimuli that were mapped onto each response could be categorised together. They argued that Bertelson's RoRR effect was simply a standard RR effect in which, although the exact stimulus had changed, the stimulus *category* was repeated, such that the stimulus-response pairing had still been primed. This was a critical insight.

Pashler and Baylis (1991) initially considered several possible accounts of the RR effect. Their perceptual speedup account predicted RR effects only when neighbouring stimuli are physically almost identical. A categorisation speedup hypothesis predicted an RR effect when a stimulus comes from the same higher-order category as its predecessor, such that the process of identifying that category is primed. The highest link hypothesis suggested transient strengthening of the S-R pathway from the stimulus category to the response, while the response-selection shortcut account suggested that a more direct link from a specific stimulus to a response (bypassing some of the intermediate stages of sensory analysis) might receive a temporary boost. Finally, Pashler and Baylis considered a response execution speedup account (essentially what we refer to here as a motor-plan persistence account) under which the response itself is facilitated whenever it repeats across trials.

With these possibilities in mind, Pashler and Baylis went on to vary the degree to which the two stimuli that were mapped to one of three possible responses shared a common category. They obtained strong RoRR effects only when the stimulus difference for a given response was trivial (i.e. two versions of the same stimulus in a different colour mapped onto a response). They found a

smaller RoRR trend when stimuli changed but remained within the same easily identifiable category (e.g. having two letters mapped onto one response, two numbers mapped to a second, and two symbols mapped onto the third). Finally, they obtained no effect at all for response repetitions involving uncategorisable stimuli (by which they meant a situation in which stimulus categories existed, but were orthogonal to response mappings, e.g. one letter and one symbol mapped to each response). Complimentary experiments showed that repeating the stimulus gave no benefit if the response changed (see also Campbell & Proctor, 1993). Hence Pashler and Baylis concluded that the locus of the first-order repetition benefit is at the stage of response selection, with repetitions producing transient links that shortcut the response selection stage.

Several groups have now manipulated whether the stimuli that are mapped onto each response can be categorised together (Campbell and Proctor, 1993; Pashler & Baylis, 1991; Soetens, 1998). Results suggest that Bertelson's (1965) RoRR effect was really just a classic RR effect masquerading as something else, because at a conceptual level the stimulus was actually still being repeated. Because RR effects were only found to be robust with stimuli that could be categorised in this way, investigating RR effects with many-to-one mappings and stimuli that could not be categorised was subsequently largely abandoned. We are aware of only one study in recent years that has shown a response-only RR effect (Notebaert & Soetens, 2003). In that case, four colours were mapped to two responses (green/yellow vs. red/blue) so it is possible that the formation of higher order categories (specifically "near chartreuse" vs. "near purple") generated this result.

Appropriate conditions for an RoRR effect?

The preceding short review indicates that behavioural measures are in fair agreement regarding the motor system's involvement in first-order sequential effects: RoRR effects do not generally occur without stimulus category repetition, implying that motor activation representing the response on trial N-1 does not (usefully) persist through to trial N in choice RT tasks. However,

while there seems little doubt that stimulus-response translation makes the largest single contribution to RR effects, there are in fact several psychophysiological findings that question the conclusion that motor persistence is irrelevant. For example, Jentzsch and Sommer (2002) reported a build up or priming of the lateralised readiness potential (LRP: an EEG component associated with the preparation and execution of a lateralised action; Coles, 1989) over multiple repetitions in a two-choice RT task. They also provided some evidence that the onset of the response-locked (R-) LRP varied with first and higher-order sequential effects. A shifted onset for the R-LRP is generally interpreted to imply a change in the duration of motor preparation, and thus that an effect is localised in the motor system (Leuthold, Sommer & Ulrich, 2004). Note, however, that the aforementioned build up of baseline activity makes it quite difficult to assess differences in LRP onset for first-order transitions (because the pre-stimulus period used for normalisation is itself being influenced).

There is also a relevant higher-order repetition effect (the benefit-only pattern, wherein alternations at positions $< N-2$ increase RT regardless of the first-order transition) which can emerge as an RoRR effect when assessed with the information-reduction procedure (Jentzsch & Leuthold, 2005; Soetens, 1998). Recent behavioural and electrophysiological experiments suggest a key role for persisting motor activations in generating this effect. To be specific, the benefit-only higher-order effect appears to stem from a process triggered by response competition: Persistent activity from trial $N-2$ generates a competing pool of motor activation when the response alternates on trial $N-1$, which in turn increases the demand for resources from a conflict-monitoring process (plausibly located in anterior cingulate cortex; Jones, Cho, Nystrom, Cohen, & Braver, 2002). This conflict-monitoring process then interferes with response selection occurring on the current trial (N), slowing the response (Dudschig & Jentzsch, 2008; Jentzsch & Leuthold, 2005). For our purposes, the key point is that the whole account implies meaningful persistence of motor plans across trials. If motor activation survives the transition from trial $N-2$ to trial $N-1$ to trigger conflict monitoring, why is it not equally robust across the transition from trial $N-1$ to trial N ?

With these findings in mind, we wondered whether RoRR effects had really been given a fair chance to emerge in the behavioural literature. In particular, we wondered whether hidden assumptions about a serial processing architecture had muddied the water. When response repetition effects first hit the headlines, the prevailing metaphor of mind was the serial digital computer. In this context, the notion of a decision stage preceding the generation of a motor plan came naturally. However, modern cognitive neuroscience tends to think in terms of massively parallel neural operations (e.g. Cisek & Kalaska, 2010). One implication of this thinking is that the notion of a motor plan that is specified only after a decision-making operation is now challenged by equally plausible accounts in which multiple motor plans could be maintained in the brain at once, with their relative strengths reflecting the moment-by-moment weighting of a decision. Several lines of evidence, including for example neural recordings from psychophysiology (Jentzsch & Leuthold, 2002; Jentzsch, Leuthold, & Ridderinkhof, 2004; Leuthold & Jentzsch 2001) and particularly primate electrophysiology (e.g. Cisek & Kalaska, 2005; Cui & Andersen 2007; Hoshi & Tanji 2007), and also the triggering effects of very loud (“startle”) stimuli (Carlsen, Chua, Summers, Inglis, Sanderson, & Franks, 2009), support the idea that more than one action plan can actually be developed and maintained in the brain in parallel.

If humans can hold more than one action plan active in their motor system, this has important implications for the predicted strength of RoRR effects that should emerge from the information-reduction procedure when applied using two-choice and three-choice RT tasks. Given the capacity to maintain multiple motor plans, a reasonable strategy in such RT tasks would be to maintain *all* action plans in as active a state as possible (i.e. just below a threshold for generating excessive erroneous responses) *throughout the block of trials*. This could explain why activating a plan on a preceding trial does not seem to speed up action-plan generation on the subsequent trial: All relevant action plans might be being held active regardless of immediate history, thus minimising the difference between a plan boosted by residual activity and one that is in its baseline (but still somewhat pre-potent) state.

Based on these considerations, we hypothesised that in order to generate RoRR effects, it might be necessary to challenge the motor system beyond its (currently unknown) capacity for parallel action planning, so that all plans could not be constantly and consistently maintained. Although increasing the number of response alternatives is traditionally thought of as a manipulation affecting stimulus-response translation, when considered within the context of a parallel action planning architecture it becomes apparent that increasing possible responses probably also affects the motor system directly. More alternatives could mean that not all such alternatives can be maintained/prepared to the same extent. The influence of the previous trial's residual motor activation might emerge in such a situation of decreased parallel preparation, because the same persisting motor activity would now provide a greater boost relative to background activity. This would follow, for example, in an architecture like the one Cisek (2006) proposed, where maintaining a greater number of potential action plans generates greater mutual inhibition from each upon the others and thus a lower baseline state.

With these ideas in mind, we set out to test our hypothesis by increasing motor load to see if an RoRR effect then emerged. Given the well-established concerns of Pashler & Baylis (1991) that RoRR effects with categorisable stimuli are just stimulus-response (S-R) RR effects in disguise, we selected stimuli from two unrelated sets/dimensions, and mapped one stimulus from each dimension onto each response. Where previous information-reduction experiments collapsed trials into Bertelson's Identical, Equivalent and Different categories, we were mindful of the subsequent literature on task switching inspired by Rogers & Monsell (1995). This work suggested to us that a single all-purpose baseline condition (Bertelson's "different" trials) built by collapsing cases where the stimulus category changed and the response changed with cases where the stimulus category repeated but the response changed was not really appropriate. Hence, for our data analysis we retained a factorial approach (considering repetitions of both stimulus category and response, separately and in interaction) as naturally implied by an information-reduction design where stimuli come from different sets. This allowed us to more fairly assess the effects of response repetitions

with and without stimulus category repetitions. Hence in our experiments, an RoRR effect was quantified by comparing a situation in which the stimulus set changed and the response repeated with a situation in which the stimulus set still changed but so did the response.

In Experiment 1, we attempted to challenge the capacity of the motor system by increasing the number of response alternatives, but critically, we did so within the information-reduction paradigm with noncategorisable stimuli, which, to our knowledge, has not previously been attempted. To pre-empt our results: we obtained a clear RoRR effect with four or more responses (contrary to most previous findings with two and three-choice tasks). We then replicated this new RoRR effect with four response alternatives in a second experiment, which generalised it with a change of response configuration and demonstrated that it did not vary with practice.

Experiment 1

For Experiment 1, we chose to manipulate load on the motor system by varying the number of response alternatives. We selected stimuli varying along two dimensions (c.f. Pashler & Baylis, 1991), choosing form and colour as our dimensions (c.f. Jentzsch & Leuthold, 2005). One stimulus from each dimension was mapped onto each of the possible responses, to ensure that the two stimuli defining any given response could not be distinguished from those mapped to the other responses using any simple categorical rule. Finally, we selected a short (50 ms) RSI in order to maximise first-order repetition benefits and attempt to limit expectancies and other higher-order effects.

Methods

Participants

Twelve participants (9 female) with a mean ($\pm$ SD) age of 22.1 ± 5.1 years took part in the experiment. Most subjects participated as partial fulfilment of a course requirement.

Apparatus & Stimuli

Participants were seated at a desk in front of a CRT monitor (1024x768 pixels, ~40x30 cm, with a vertical refresh rate of 100 Hz) with the screen at a distance of ~30 cm. They responded using a standard qwerty keyboard. The experiment was programmed in C++, with a PC controlling presentation of the stimuli and recording responses. The imperative stimuli consisted of eight coloured squares (black, pink, red, blue, yellow, green, purple and grey squares; 100 pixels i.e. $\sim 7.6^\circ$ visual angle across) and eight religious symbols (the Christian Ichthys, the Christian Cross, the Taoist Ying/Yang, the Jewish Star of David, the Sikh Khanda, the Islamic Star and Crescent, the Buddhist Wheel of Life and the Hindu Aum; see Figure 1). All were contained within a region of 100 pixels, i.e. $\sim 7.6^\circ$ visual angle, square. They appeared centred on the screen, at fixation. Participants used the “Z”, “X”, “C”, “V”, “M”, “,” , “.” and “/” keys to make their responses, using their left little, left ring, left middle, left index, right index, right middle, right ring and right little fingers respectively. One coloured square and one symbol were mapped to each key/finger.

<INSERT FIGURE 1 AROUND HERE>

Design, Procedure & Data Analysis

The experiment had a three-factor repeated-measures design. The three factors were *stimulus-response alternatives* (2, 4 or 8 possible responses), *stimulus-dimension transition* (repeat/change) and *response transition* (repeat/change). The first factor was blocked, with the

order of these blocks counterbalanced. The remaining two factors were randomly ordered in each block of trials.

Unlike many investigations of sequential effects, our design deliberately specified two-trial “episodes”, consisting of a pair of stimuli and their responses, such that the sequence of *transitions* (ignoring the transitions between our imposed episodes) was random without replacement. This procedure provides somewhat better control over the frequency of different kinds of transition in a block; it is less prone to the deviations from equal likelihood that can result from randomisation based on just the stimulus (rather than transition) types. This underlying structure was invisible to participants, who simply experienced a succession of stimuli, in which all stimuli were presented equally often in a block of trials.

With eight colour and eight symbolic stimuli there were $16 \times 16 = 256$ possible kinds of episode, consisting of the full factorial combination of the sixteen different stimuli with one another. However, the two and four-choice conditions only used a subset of the stimuli (yielding $4 \times 4 = 16$ and $8 \times 8 = 64$ possible episodes, respectively). In these cases, participants responded using only their index fingers (two choice) or their index and middle fingers (four choice) with none of the remaining stimuli mapped to ring or little finger responses being presented. Our decision to randomise episodes, rather than randomising stimuli, does not introduce any complications for the basic rates of stimulus presentation: Because all possible episodes were incorporated equally often in all conditions, every kind of stimulus was always presented an equal number of times in a block (with the exception of episodes that were repeated due to an error; see below).

Episodes were used to construct four different conditions based on the relationship between the first and second trials, representing the 2×2 factorial combination of stimulus-dimension transition and response transition. For example, the [stimulus-dimension transition = change / response transition = repeat] condition consisted of trials from the Ichthys-black, black-Ichthys, Cross-pink, pink-Cross, Ying-Yang-red, red-Ying-Yang (...etc.) episodes. For the eight-choice block, each of the 256 kinds of episode was repeated once in a block of 256 episodes. Because non-

repetitions are more likely than repetitions with > 2 responses, this procedure yielded 16 of each kind of response-repetition episode and 112 of each kind of non-repetition. The four-choice block had 64 kinds of episode, each repeated twice, to yield 16 of each kind of response-repetition episode and 48 of each kind of non-repetition. Finally the two-choice task had 16 kinds of episode each repeated four times, yielding 16 episodes in each condition.

In our analyses, we only made use of the data recorded on the second trial of an episode. When the first trial of an episode yielded an incorrect response, the episode was rejected, but repeated by tagging it on to the end of the block. Hence our analysis only includes trials where the preceding stimulus was correctly responded to. Our dependent variables were RT and error rate. To counteract any effect of skewed RT distributions, the median rather than the mean value of RT was determined for each participant in each condition. An error was recorded when an incorrect response was made to the second trial of an episode.

For inferential statistical analyses (conducted in SPSS v19.0, IBM; $\alpha = 0.05$) we used factorial repeated-measures ANOVAs with Greenhouse-Geisser corrections for sphericity when assessing RT data. For error data, we used generalized linear mixed models (GLMMs) with a logit link function and a random intercept term to capture subject-level variation¹. For tests of GLMM fixed effects, we specified model-based covariance estimates with df fixed for all tests. To further maintain a concise presentation, we do not generally report all main effects or interactions in our ANOVAs/GLMMs when highest-level interactions were obtained (and consequently explored in subsequent analyses by breaking the data down).

Participants were given three practice blocks in order to become accustomed with the task at the start of the experiment: Colours alone, symbols alone and both mixed together. These blocks included all eight possible responses and sixteen possible stimuli, and contained 64, 64, and 256 episodes respectively. Participants then commenced with the three experimental blocks. Each stimulus remained on screen until a response was made, after which there was a response-stimulus

¹ We considered including random terms for slopes, but these models generally yielded many zero estimates for random effect sizes, and had higher df-adjusted estimates of model goodness of fit.

interval of 50 ms, with the first 20 ms of the RSI containing a red flash over the entire screen whenever an error was made. Participants were given an opportunity to rest every 32 episodes (64 trials). The whole experiment lasted between 45 minutes and an hour.

Results and Discussion

<INSERT FIGURE 2 AROUND HERE>

Figure 2 shows RTs and error rates for Experiment 1. With two response alternatives, there is a clear response-repetition effect when stimulus dimension repeats (i.e. identical episodes, e.g. blue square then blue square, are faster and less error prone than episodes where response changes within the same stimulus dimension, e.g. blue then yellow squares). However, there is no response-only RR effect, as measured on trials where stimulus-dimension changes (i.e. comparing equivalent episodes, e.g. blue square then Star of David, to episodes where everything changes, e.g. blue square then Khanda). However, the situation is rather different in blocks with four or eight response alternatives. Now, a response-only RR effect is present in RTs and errors when stimulus dimension changes (as well as the standard response-repetition effect when stimulus dimension has been repeated).

These observations were confirmed via factorial ANOVA/GLMM. For RT data, a three-way interaction (stimulus-response alternatives x stimulus dimension transition x response transition; $F_{[1.6, 17.3]} = 8.56$, $MSE = 3656$, $p = 0.004$) was followed up with three 2x2 ANOVAs, one for each number of stimulus-response alternatives. All showed significant interactions (two-choice: $F_{[1, 11]} = 8.24$, $MSE = 3077$, $p = 0.015$; Four-choice: $F_{[1, 11]} = 42.56$, $MSE = 5229$, $p < 0.001$; Eight-choice: $F_{[1, 11]} = 17.20$, $MSE = 6765$, $p = 0.002$) with post-hoc paired t-tests showing response-repetition effects regardless of number of response alternatives when stimulus dimension repeated (all $t_{[11]} \geq 5.48$, $ps < 0.001$). Critically, however, a response-only RR effect, which was absent with two responses (11 ms

difference, $t_{[11]} = 0.52$, $p > 0.05$) emerged with four (121 ms difference, $t_{[11]} = 2.60$, $p = 0.025$) or eight (195 ms difference, $t_{[11]} = 5.35$, $p < 0.001$) choices.² While trends in the error data were consistent with the pattern of RTs, here the GLMM three-way interaction between all factors did not reach significance.

Although this new RoRR effect with four or more response alternatives and no category repetition was striking, we were somewhat concerned that it might reflect peripheral biomechanical factors. The conditions with more alternatives made use of the middle, ring and little fingers, in addition to the index fingers used in two-choice conditions, so we wondered whether pressing the same key twice in a row was for some reason more advantageous (or at least less costly) specifically in these response configurations. For example, in our two choice-conditions, response alternations were always made by using the homologous finger of the opposite hand, so represented a kind of repetition, whereas this was true for only a (decreasing) proportion of four and eight choice alternation trials.

To assess this possibility, we extracted only those trials that had involved the index fingers (for *both* trials of an episode) from four and eight-choice conditions. If biomechanical factors were responsible for the appearance of the RoRR effect, no effect should be evident in this subset of two-trial episodes. In fact, response-only RR effects emerged from this analysis with a similar magnitude to those in the full data set (differences of 132 and 127 ms for four and eight choice RoRR effects respectively, compared to 121 and 195 ms in the full data set). However, the analysis necessitated a large reduction in the number of episodes that could be included (we were reduced to 8 episodes per condition per participant in the four-choice conditions, and just 4 episodes per condition in the eight choice cases) which may explain why these trends were not found to be statistically significant (with p values of 0.09 and 0.40 for four-choice and eight-choice analyses respectively).

² Other results included a main effect of number of stimulus-response alternatives in the three-way ANOVA ($F_{[2.0, 21.5]} = 21.40$, $MSE = 21229$, $p < 0.001$) indicating generally slower responding with more response alternatives, as would be expected.

To summarise the results of Experiment 1: We obtained clear evidence that a response-only RR effect could emerge with as few as four response alternatives, contrary to previous findings with two or three responses. There was nothing in the data to suggest that this result reflected biomechanical differences that came in to play only as the number of alternatives increased, or some special influence of homologous alternations in two-choice conditions, because similar trends were found in subsets of four and eight-choice data derived exclusively from the two fingers used in two-choice conditions. However, because this result represents a departure relative to the previous literature, we thought it prudent to replicate it in a second experiment.

Experiment 2

In Experiment 2, we made use of the less onerous four-choice conditions from Experiment 1 in order to produce a conceptual replication. We also took the opportunity to check that the result was not highly specific to our experimental conditions in Experiment 1, by varying response configuration in a one-hand versus two-hand comparison. Finally, we were concerned by early reports (Rabbitt, 1968) suggesting that practice had strong modulatory effects on the RoRR effect (which became significant there only after substantial practice). Hence in Experiment 2 we had participants engage in a larger number of trials, so that we could test whether our novel RoRR effect, which we had obtained without any potential categorisation confound, was stable across different stages of learning.

Methods

Methods were identical to Experiment 1 except as follows.

Participants

Twenty participants (15 female), mostly undergraduate psychology students, with a mean age of 24.3 (SD 3.9) took part in the experiment. Undergraduates received course credit in exchange for their participation.

Apparatus & Stimuli

We used stimuli from the four-choice conditions of Experiment 1 (i.e. those mapped to the index and middle fingers in that experiment: The Taoist Ying/Yang, the Jewish Star of David, the Sikh Khanda, the Islamic Star and Crescent, plus red, blue, yellow and green squares). Participants sat at a distance of ~50 cm from the screen, with a corresponding decrease in stimulus size on the retina relative to Experiment 1 (100 pixels was now ~4.6° visual angle). For the ten participants who responded using both hands, red / Ying-Yang and blue / Star of David stimuli were mapped to the keys “C” and “V” pressed with the middle and index fingers of the left hand respectively. Meanwhile, yellow / Khanda and green / Star and Crescent stimuli were mapped to the keys “M” and “,” pressed with the index and middle fingers of the right hand respectively. A second set of 10 participants placed all four fingers of their right hand across the keys “V”, “B”, “N”, “M”, mapped to the colours red, blue, yellow and green, together with the symbols Ying-Yang, Star of David, Khanda and Star and Crescent, and pressed with the index, middle, ring and little fingers respectively. We included this manipulation to check that our RoRR result generalised to a different hand configuration.

Design, Procedure & Data Analysis

This experiment comprised four factors in a 2 x 2 x 2 x 2 mixed factorial design. Three of these factors, *stimulus-dimension transition* (repeat or change), *response transition* (repeat or change) and *practice* (early vs. late) were manipulated within subjects, and the final factor, *hands*

(one vs. two) was manipulated between subjects. The first two factors were randomised within blocks as per Experiment 1. For these, the eight different stimuli (four colours and four symbols) gave rise to 64 possible pairs, which were divided into four different repetition conditions that represented all combined levels of the stimulus dimension and response factors. Each experimental block contained a total of 128 episodes (two repetitions of the 64 possible episodes), and participants completed eight such blocks. The first four blocks generated a 512-episode early practice set, and the remaining four blocks generated the equivalent late practice set, with 64 episodes in each of the two kinds of repetition condition and 192 episodes for the non-repetition conditions in each half of the experiment.

Each participant first practised two short blocks of only colour stimuli that comprised 64 episodes, then two blocks of only symbols (also 64 episodes) and finally one block of both colours and symbols together (i.e. as presented in the experimental blocks; again, 64 trials). Then they moved on to the experimental blocks. Timing and other aspects of stimulus presentation were identical to Experiment 1.

Results and Discussion

<INSERT FIGURE 3 AROUND HERE>

The results of our final experiment are shown in Figure 3. The graphs on the left show sessions early on in practice, while late practice sessions are shown on the right. The upper graphs show performance from the group using all four fingers of the right hand, while data from the two-hand group are shown in lower graphs. The pattern of RT data is similar in all cases. There is a large RR effect when both stimuli in an episode shared a stimulus dimension. For example, a green square followed by a red square, or a Ying-Yang symbol followed by the Star of David, led to slower RTs compared to the exact repetition of a stimulus. Importantly, there is also a small but consistent RoRR

effect when the stimulus dimension changed across the two-trial episode. For example, a green square followed by a Ying-Yang symbol (stimulus-dimension change, response changes) yielded slower RTs than a red square followed by a Ying-Yang symbol (stimulus-dimension change, response repeats). Error data mirrored RT effects when the stimulus dimension repeated, but were less consistent with regards to the RoRR effect when stimulus dimension changed.

A mixed-measures (three within, one between) 2x2x2x2 ANOVA on the RT data showed a significant main effect of practice ($F_{[1, 18]} = 22.04$, $MSE = 1789$, $p < 0.001$), reflecting the fact that participants were on average 32 ms faster to respond to stimuli in the second half of the experiment compared to earlier blocks of trials. More critically, the only significant interaction was the two-way interaction between stimulus-dimension transition and response transition ($F_{[1, 18]} = 151.36$, $MSE = 3340$, $p < 0.001$). Hence data were collapsed across the non-interacting factors (practice and hands), with separate post-hoc paired t-tests then applied to test for RR and RoRR effects with and without stimulus dimension repetition respectively. Not surprisingly, participants were significantly faster to respond when everything repeated than when stimulus dimension repeated and response changed ($t_{[19]} = 15.03$, $p < 0.001$), demonstrating the classic RR effect. More importantly, participants were also significantly faster to respond when stimulus dimension changed but response repeated than when everything changed (mean difference 35 ms, $t_{[19]} = 3.10$, $p = 0.006$), indicating a successful replication of the RoRR effect in the RT data. Although not indicated by an interaction, we felt that it was theoretically important to demonstrate that this RoRR effect was robust in both hand configurations individually, so we also assessed the effect in each of the two groups. The effect was significant in the one-hand group (mean difference = 24 ms, $t_{[9]} = 2.51$, $p = 0.034$) and marginal in the two-hand group (mean difference = 47 ms, $t_{[9]} = 2.23$, $p = 0.053$). Given that both comparisons might reasonably have been considered as one-tailed hypotheses, and that the two-hand condition has already yielded a significant effect in Experiment 1, this provides fairly strong evidence that the RoRR effect is present in both hand configurations.

An equivalent GLMM on the error data yielded a similar pattern of significance, although the main effect of practice was not obtained, with a significant effect of hands emerging in its place [$F(1, 144) = 5.08, p = 0.026$] due to higher mean errors for the participants responding with one hand (5.3%) rather than two hands (2.9%). This was slightly unexpected, given the additional scope for homologous finger substitutions, which are known to occur in typing (Lessenberry, 1928), when using two hands. As in the RTs, the only significant interaction was a 2x2 interaction between stimulus-dimension transition and response transition ($F(1,144) = 59.22, p < 0.001$) but in the error data (collapsed across hand and practice) post-hoc comparisons revealed that the clear RR effect when stimulus dimension repeated ($F(1,144) = 57.39, p < 0.001$) was not supplemented by any RoRR effect when stimulus dimension changed ($F(1,144) = 1.34, p > 0.05$), with a very slight (0.6%) trend running in the opposite direction.

To summarise the results of Experiment 2, the RT data demonstrated an RoRR effect consistent with that obtained in Experiment 1 with four response alternatives. Although the error data did not reveal a similar effect, there was no statistically robust evidence to suggest a speed-accuracy trade-off, i.e. a possible strategic change driving the RT result. Although the size of the RoRR effect appeared reduced in this experiment compared to the equivalent conditions of Experiment 2 (ranging from 20 to 55 ms here, rather than >100 ms there) the ANOVA provided no evidence that the effect was being modulated by task experience. This was not trivial, given that practice had a clear and reliable overall effect on RTs across our early/late epochs. There was also no evidence that the RoRR effect was dependent on one particular hand configuration. Hence we conclude that the RoRR effect is a relatively robust result with four or more response alternatives.

General Discussion

In these two experiments, we set out to test the idea that a response-only response repetition effect might emerge in choice RT tasks if the motor system was challenged (in terms of its

capacity for parallel action representation) such that not all task-relevant action plans could be maintained throughout an experimental block. To this end, we made use of the information-reduction procedure (Bertelson, 1965) in order to isolate RoRR effects. We deliberately selected two stimuli for each response that did not differ from all other stimuli according to some simple rule, in order to exclude not just repetitions of a stimulus, but also repetitions of a stimulus category (Pashler & Baylis, 1991). We attempted to challenge the capacity of the motor system (which we presumed to be capable of some degree of parallel planning) by varying the number of possible responses (Experiment 1), and then verified that the emergence of an RoRR effect with four or more response alternatives was not specific to a particular response configuration or stage of task acquisition (Experiment 2).

Our key finding was that repeating the response from trial N-1 on trial N can speed that response even when the stimulus has changed. This was established in comparison to a condition involving a closely matched stimulus change, but where the response also changed. Consistent with past research (Campbell & Proctor 1993; Pashler & Baylis, 1991; Smith, 1968) this response-only response-repetition effect was not observed with less than four response alternatives (Experiment 1). However, it was reliably obtained with four or more response alternatives (Experiments 1 and 2). The logic of the information reduction procedure suggests strongly that the locus of our new response-only RR effect is motoric. This follows because neither the exact stimulus, nor some higher-order pre-existing set to which the stimulus belongs, nor any other aspect of the previous S-R pairing aside from the response is being repeated, and yet RT improves.

Previous behavioural accounts of first-order repetition effects have tended to identify a primary locus at the stimulus-response translation stage (e.g. Bertelson, 1963; Campbell and Proctor, 1993; Kornblum, 1969; Pashler & Baylis, 1991; Soetens, Boer & Hueting, 1985). Our result in no way contradicts this finding; we simply demonstrate that an additional influence of the motor system's state on trial N-1 can be revealed when circumstances are appropriate. The simplest account would be one in which this motoric effect is additive with RR effects that arise at different processing

stages. Hence in our experiments, the sizeable classic RR effect, found when both stimulus and response are repeated, can be conceived of as (mainly) an S-R translation shortcut, plus, where conditions permit, an RoRR contribution. Our data are broadly consistent with this account, because where RoRR effects emerge (in the four and eight-choice conditions of Experiment 1) the overall RR effect also increases in size by at least as much. In fact, the increase in the RR effect is numerically larger than the emerging RoRR effect (see Figure 2).

These considerations provoke a slight reinterpretation of some previous data seeming to favour an S-R translation locus for the RR effect, specifically the interaction between the RR effect and the number of response alternatives (e.g. Biederman & Stacy, 1974; Hyman, 1953; Kornblum, 1975). To make inferences via additive factors logic, it is useful to make an assumption about the locus of one of two effects under consideration (so that the other effect can, if interacting, be assigned the same locus). The effect of the number of response alternatives is typically considered to reflect increased difficulty of response selection, a very reasonable (and probably largely correct) assumption. However, the logic presented in our rationale makes it clear that increasing the number of response alternatives could also be increasing RT via a load on the motor system. If the motor system has the capacity to maintain more than one plan across a block of trials, it is likely to do so to a greater extent when there are many response alternatives. Hence the classic interaction with the RR effect may well actually represent *shared* loci at both decision and motoric stages of information processing.

The notion that response-specific activations persevere from one trial to the next in choice RT tasks is broadly compatible with reports showing a build-up of the lateralised readiness potential across trials (Jentzsch & Sommer, 2002). It is also consistent with evidence that the persistence of motor activation can trigger response-conflict monitoring processes giving rise to higher-order sequential effects (Dudschig & Jentzsch, 2008; Jentzsch & Leuthold, 2005). Motor persistence (or rather the apparent requirement to counteract it) is also an important component of some current models of task switching, which often make use of choice RT tasks, but with the twist that different

responses must be made to an identical stimulus as a result of periodic changes in response set (Druey & Hübner, 2008; Rogers & Monsell, 1995).

Looking beyond the choice RT literature, there are several other experimental approaches that have provided evidence for the persisting influence of motor parameters on subsequent trials. For example, Jax and Rosenbaum (2007) found that when reaching to a target, reach trajectory was more curved when participants had just experienced a trial in which they had been required to avoid (curve around) an obstacle, even though the obstacle was no longer present. In fact, they found an accumulation of such tendencies across trials (i.e. a form of higher-order sequential effect). Similarly, Dixon and Glover (2009) found that when participants reached to grasp disks of various diameters, the grip aperture on the previous trial was assimilated so as to influence the grip aperture on the current trial during the grasp phase (whereas stimulus transitions from the previous trial generated perceptual contrast effects, evident during the reach phase).

Jax and Rosenbaum's (2007) and Dixon and Glover's (2009) reaching and grasping tasks also prompt us to consider another prediction about motor perseveration: That decisions on trial N should be biased by the action that was performed on trial N-1. In this paper, we have focussed on the potential speed benefit of a persisting motor plan, and considered errors only in terms of rejecting a speed-accuracy trade off account of our data. However, with more than two alternatives there is a clear prediction that when errors occur in non-repetition trials, people should be biased towards repeating the previous action. Our tasks all had very low error rates, which makes them poorly designed to test this prediction (which is why we did not attempt such an analysis). However, tasks better designed to test this prediction (for example making use of more ambiguous stimuli to promote response uncertainty) could address this issue in the future.

In the introduction, we cited evidence suggestive of parallel motor planning (reviewed in Cisek & Kalaska, 2010) and proposed that persisting motor activity would be less relevant, i.e. less likely to influence subsequent actions, if several potential actions were being maintained. Because the emergence of the RoRR effect followed from a clear hypothesis about the conditions in which it

might be found, we have tended to be somewhat cavalier in proclaiming that the RoRR effect reflects the existence of persisting actions plans. However, there are other possible accounts of the RoRR effect in our data. While we took pains to rule out repetition of a stimulus category that might prime an S-R link, it seems possible that our effect represents a kind of reverse associative priming, whereby performing an action (in response to whatever stimulus) primes all the associated stimuli, leading to a stimulus-based benefit on the next trial regardless of which of them appears. However, Experiment 1 provides some strong evidence against claims of this kind, because such priming of stimuli should have been equally potent in the two-choice block, yet no RoRR effect emerged there.

A more nuanced objection is that while we have demonstrated an influence of the prior motor response on the current trial, we have not demonstrated the mechanism of this influence, and in particular we have no direct evidence that a plan is persisting in motoric regions of the brain. In principal, a memory for the last action could be being stored at a non-motoric locus, and from there helping to re-activate the equivalent motor activity on the next trial. This idea is similar to proposing the rapid formation of an expectation about the subsequent motor act (although such an expectation is probably not arising at the explicit level; c.f. Jax & Rosenbaum, 2007; Tubau & López-Moliner, 2009). In partial response to this, we have already described LRP evidence suggesting that motor activation can build up across trials (Jentzsch & Sommer, 2002). However, the LRP can reveal only between-hemispheric differences, and our data suggest that persistence may be best captured with more than two response alternatives. One possible approach with both the temporal and spatial resolution necessary to demonstrate persisting motor activation in the brain would be to use transcranial magnetic stimulation to trigger motor evoked potentials (MEPs: evoked muscular activations that can provide an index of motor preparation). MEPs can track activations across time for two discrete actions with the same hand (e.g. Makris, Grant, Hadar & Yarrow, 2013; Makris, Grant, & Yarrow, 2011; Hadar, Makris & Yarrow 2012) and this approach could easily be extended to track four action plans from two hands in the period after a response has been made.

We should also consider the possibility that RoRR effects are not emerging de novo when motor load is increased to four or more response alternatives, but might in fact be present in two and three-choice tasks, but be being counteracted by an opposite influence, for example a high-level expectation of alternation (c.f. Kirby, 1976). Such an expectation might be cancelling motor persistence directly, by boosting alternative plans within the motor system, or operating at some other cognitive locus but with the net effect of cancelling out the motoric RoRR effect. Another possibility, raised by our reviewers, is that it is not the increase in motor alternatives, but rather the increase in the load on memory (i.e. in having to remember all the different stimulus-response associations) that caused an RoRR effect to emerge with four or more responses (and thus eight or more stimuli). Perhaps cognitive resources are used in order to suppress motor perseveration (which might be viewed as error promoting and therefore undesirable); it is possible that these resources cannot be mustered under high memory load. These kinds of account don't really challenge our basic finding (i.e. that an RoRR effect has, for some reason, emerged) but do imply that it may have little to do with the brain's capacity for parallel action planning as we have suggested. More work will be required in order to assess these ideas properly.

Finally, in a somewhat similar vein, it might be objected that our ability to demonstrate an RoRR effect may just reflect our decision to abandon the traditional ternary division of data in information-reduction approaches (i.e. identical/equivalent/different trials) in favour of a 2x2 division that divides different-response trials according to their stimulus transition properties. Taking an average of the two kinds of non-response-repetition trials would provide a consistently lower value of RT against which to measure RoRR trials, and would thus mitigate the effect. However, we would argue that using a better matched non-repetition control condition is a strength, not a weakness of our work: We measure both classic RR and RoRR effects in situations where the stimulus set transition has been matched, and thus control for a possible task-switching confound. In any case, our RoRR effect is measured in the same way in all experiments and conditions, but only emerges in the particular circumstances we have described.

In conclusion, we investigated why previous researchers have generally failed to generate a convincing response-only response repetition effect, and thus to demonstrate any perseveration of motor activity, in choice RT keying tasks. By confronting the motor system with a larger set of potential movements, we were able to show that the RoRR effect can in fact be found in choice RT even when the stimuli mapped to each response are hard to group categorically. This is consistent with other demonstrations of motor priming in reaching and grasping tasks, and also the inclusion of motor persistence in theoretical accounts of other cognitive effects, such as higher-order sequential effects and task switching. We consider the RoRR effect that we have uncovered here to have potential practical importance, because most real-life situations requiring speeded motor decisions present a range of potential actions, rather than just two or three alternatives. For example, the anecdotal ability of sportspeople to catch their opponents out through establishing false expectations could have a basis that is not just cognitive in nature, but also partly motoric. We thus look forward to uncovering more about the relative contribution and nature of this effect in future research.

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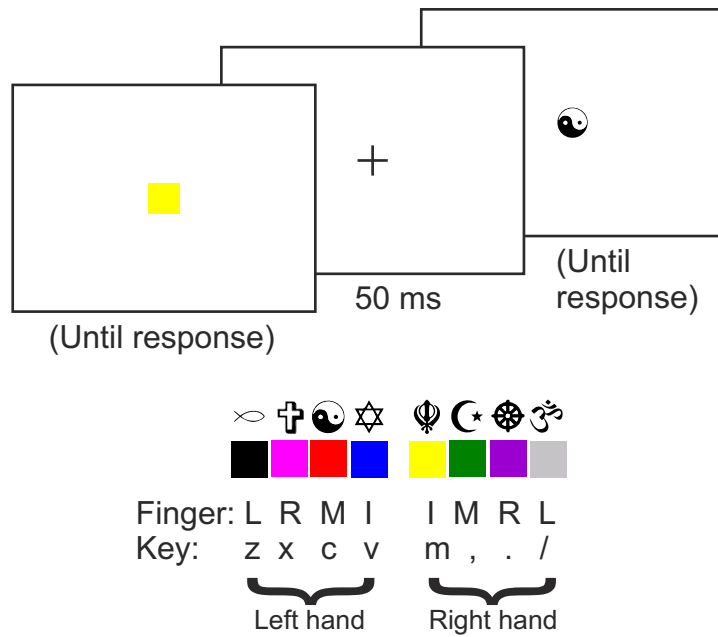
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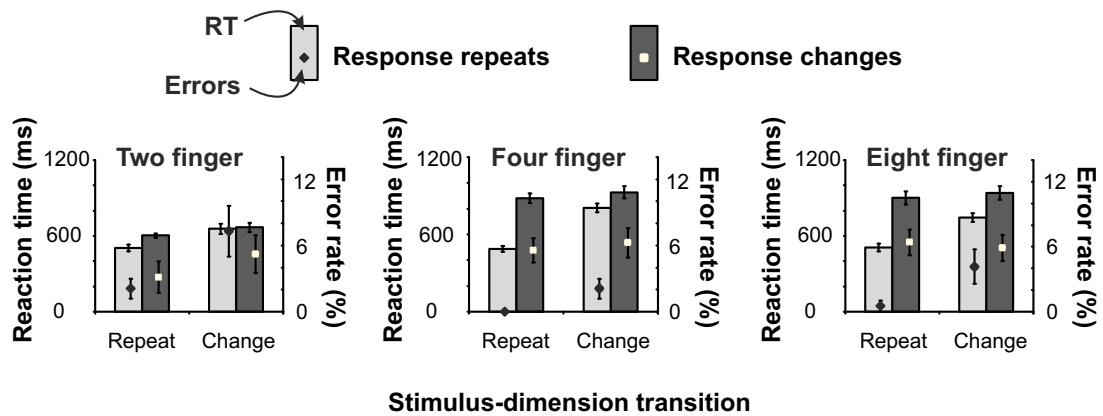
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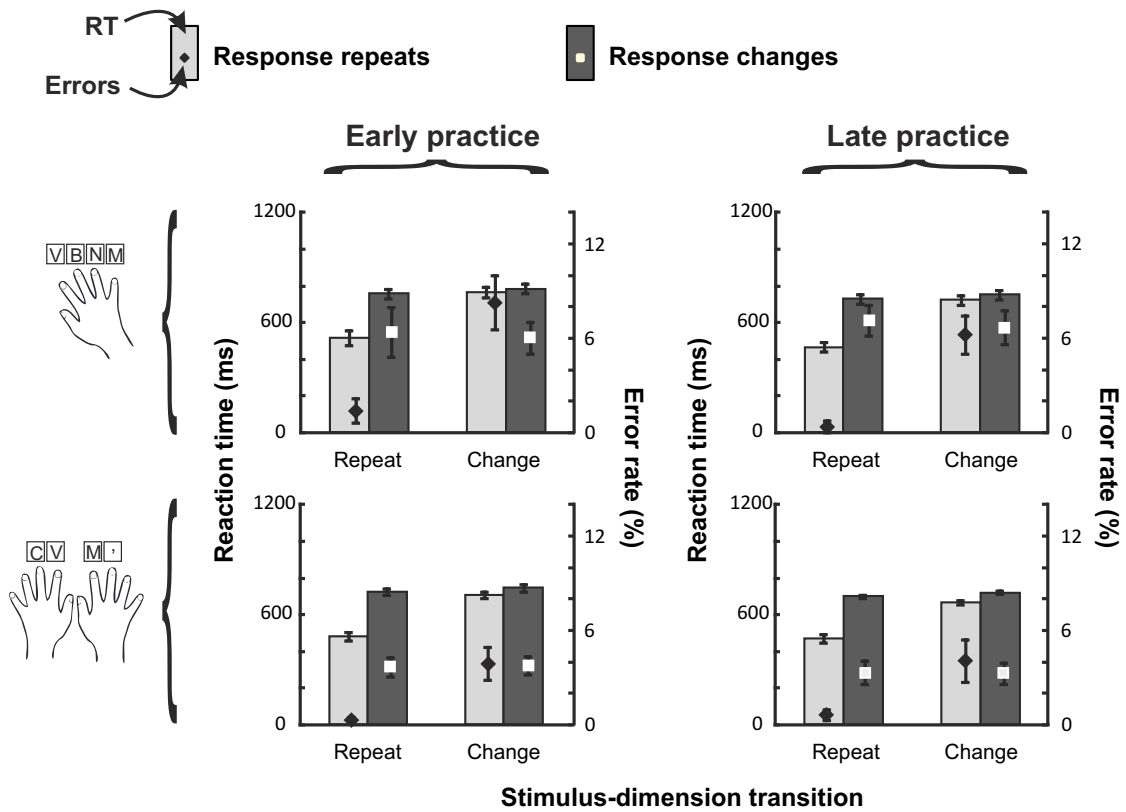
Legend to Figure 1

Schematic of experimental procedures. An example episode from Experiment 1 or 2, showing a trial from the stimulus-dimension changes / response changes condition. Response mappings in Experiment 1 are shown at the bottom of the panel (the central four mappings were also used in the two-hand conditions of Experiment 2). For black and white versions of the figure, coloured squares are black/pink/red/blue/yellow/green/purple/grey (from left to right). Finger is abbreviated to (I)ndex, (M)idle, (R)ing and (L)ittle.



Legend to Figure 2

Results from Experiment 1. Increasing response complexity (two vs. four vs. eight possible responses) is shown in the three graphs, from left to right. Filled columns represent group means of median RTs (scaled to the left-hand y axis), while free-floating squares/diamonds represent group-mean percentage errors (scaled to the right-hand y axis). In each graph, the classic (stimulus and response) response-repetition effect is evident as the difference between the two columns/points grouped together on the left, while the response-only response repetition effect is shown by the difference between the two columns/points on the right. Error bars denote standard errors of the means.



Legend to Figure 3

Results from Experiment 2. The four graphs denote the 2x2 combination of increasing time on task (early vs. late practice, from left to right) and changing response configuration (one vs. two hands, from top to bottom). Filled columns represent group means of median RTs (scaled to the left-hand y axis), while free-floating squares/diamonds represent group-mean percentage errors (scaled to the right-hand y axis). In each graph, the classic (stimulus and response) response-repetition effect is denoted as the difference between the two columns/points grouped together on the left, while the response-only response repetition effect is shown by the difference between the two columns/points on the right. Error bars denote standard errors of the means.