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Through the portal: Effect anticipation in the central bottleneck

Robert Wirth [a,*], Roland Pfister [a], Markus Janczyk [b], Wilfried Kunde [a]

[a] Department of Psychology, Julius Maximilians University of Würzburg, Röntgenring 11, 97070 Würzburg, Germany
[b] Department of Psychology, Eberhard Karls University Tübingen, Schleichstraße 4, 72076 Tübingen, Germany

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ABSTRACT

Ample evidence suggests that motor actions are generated by mentally recollecting their sensory consequences, i.e., via effect anticipations. There is less evidence, though, on the capacity limitations that such effect anticipations suffer from. In the present paper we aim to overcome shortcomings of previous research on this issue by extending the set of empirical indicators of effect anticipations and by using trial-wise instead of block-wise manipulations. In four experiments using the locus of slack- and the effect propagation-logic, we found conclusive evidence for effect anticipation taking place in the capacity-limited central bottleneck. These findings extend previous research suggesting an overlap of a "response selection" process as assumed in traditional stage theory and effect anticipation processes as assumed in effect-based ideomotor models of action control.

1. Introduction

1.1. Sensorimotor and ideomotor approaches

"Why did the chicken cross the road?" The most common answer to this question – "to get to the other side" – highlights the importance of action goals for how (human) agents select particular actions and the corresponding bodily movements. Although there is quite a consensus about this, not all traditions of psychological theorizing assume a function of such goals in the very generation of motor acts, i.e., for the immediate control of bodily movements. In particular, sensorimotor, stimulus-oriented approaches conceptualize motor control mainly in terms of responding to external stimulation and consider goals to be unrelated to the mechanics of generating a motor act (Massaro, 1990; Sanders, 1998). More precisely, these theories often assume a series of exogenously initiated, consecutive stages: Stimuli are encoded in a perceptual stage, which is followed by a central stage that is mainly in charge of response selection, even though the exact mechanisms of response selection are not specified. Finally, a motor stage controls response initiation and execution (e.g., McClelland, 1979; Sanders, 1980; Smith, 1968). By contrast, ideomotor, effect-based models emphasize that actions are selected and initiated endogenously by anticipating the outcome that one intends to achieve (Greenwald, 1970; Hoffmann, 1993; Hommel, Müsseler, Aschersleben, & Prinz, 2001; James, 1890; Lotze, 1852; Prinz, 1987), what in turn activates the suited motor patterns to produce the intended goals.

At first glance, these two approaches appear as mutually exclusive. However, because they focus on different aspects of action control, this is not necessarily true. Whereas ideomotor models provide a mechanism that explains how actions are selected and initiated, sensorimotor models stress the sequence of information processing stages irrespective of the stages' mechanistic features. Importantly, within the framework of sensorimotor models, researchers have developed a sophisticated set of methods to locate any type of process within one of the assumed stages. By combining the parsimonious mechanisms of ideomotor theory with the sensorimotor-based methods, previous studies set out to reconcile the two apparently separate views on action control (Kunde, Pfister, & Janczyk, 2012; Paelecke & Kunde, 2007).

In these studies, participants made speeded responses to a stimulus, and each response predictably triggered an action effect. These action effects shared a common dimension with the response (e.g., left vs. right responses triggering left or right effects on the computer screen). The manipulation of *response–effect* (*R–E*) *compatibility* typically yields slower responses when actions and effects are (spatially) incompatible rather than when they are compatible (Ansorge, 2002; Badets, Koch, & Toussaint, 2013; Chen & Proctor, 2013; Janczyk, Yamaguchi, Proctor, & Pfister, 2015; Keller & Koch, 2006; Kunde, 2001, 2003; Kunde, Müsseler, & Heuer, 2007; Pfister & Kunde, 2013; Pfister, Dolk, Prinz, & Kunde, 2014; Shin & Proctor, 2012; Yamaguchi & Proctor, 2011). As the action effects are not physically present at the response time (RT) measurement, but only appear after the response, it seems reasonable that they were indeed represented prior to movement onset. In other words, the action effects were anticipated.

These studies already used the methods that will be introduced in the next section, and their results suggested the anticipative mechanisms of ideomotor theory to coincide with the central stage of response

* Corresponding author.
E-mail address: robert.wirth@uni-wuerzburg.de (R. Wirth).

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selection that is proposed by sensorimotor approaches. Yet, these previous studies do not yet allow for a definite answer to the question of whether or not ideomotor effect anticipations might indeed be the mechanistic content of the response selection stage, and the present set of experiments was designed to further corroborate this hypothesis. We will therefore describe the methodological toolbox of sensorimotor approaches in the next section, followed by a summary of two critical open questions that call for empirical clarification.

1.2. Mapping behavioral effects to stages

Determining in which of the three stages of information processing a behavioral phenomenon of interest resides is possible within the framework of the Psychological Refractory Period (PRP) paradigm (e.g., Janczyk, 2013; Janczyk, Augst, & Kunde, 2014; Janczyk, Dambacher, Bieleke, & Gollwitzer, 2015; McCann & Johnston, 1992; Miller & Reynolds, 2003; Pashler, 1984, 1994; Pashler & Johnston, 1989; Ruthruff, Miller, & Lachmann, 1995; Van Selst & Jolicoeur, 1994). In the PRP paradigm, participants perform two independent tasks (Tasks 1 and 2) in close temporal succession, and the imperative stimuli of both tasks appear with a varying stimulus onset asynchrony (SOA). The PRP effect denotes the slowdown of responses to the second stimulus with a short SOA as compared to a long SOA (for comments on exceptions to the PRP effect, see Janczyk, Pfister, Wallmeier, and Kunde (2014)). In the well-known central-bottleneck model, this is explained by assuming the central response-selection stage to be capacity-limited, in the sense that two tasks cannot entertain this stage simultaneously (thus a central "bottleneck"; Pashler, 1994; see Fig. 1), while the other stages can run in parallel with other stages. With a short SOA, the central process of Task 2 therefore is delayed because the bottleneck is still occupied by the central process of Task 1, which ultimately results in longer RTs in Task 2. With a long SOA, both tasks are temporally more separated, and their central processes have little or no overlap. Consequently, responses to the second task are faster at long as compared to short SOAs.

This paradigm also allows for mapping behavioral effects that an experimental manipulation evokes onto one of the information processing stages by means of two experimental approaches: The *locus of slack*-logic and the *effect propagation*-logic. To use the *locus of slack*-logic (Schweickert, 1978), the experimental factor of interest is implemented in Task 2. If then RTs of Task 2 (RT2) are affected at long SOAs, but not at short SOAs, this experimental manipulation appears to affect the perceptual stage (cf. Fig. 1): At long SOAs, the longer perceptual stage of Task 2 directly lengthens RT2, but at short SOAs, the longer perceptual stage is compensated for by stretching into the idle time created by the delay of the central stage (the *cognitive slack*). In statistical terms, this pattern of results is an underadditive interaction of SOA and the factor of interest. If responses to the second task are equally affected at all SOAs (i.e., additive effects of SOA and the factor of interest), the experimental manipulation must affect the central stage or the later motor stage, as lengthening in these stages cannot be compensated for by the cognitive slack.

In this latter case, the *effect propagation*-logic can be used to further differentiate between the motor stage and earlier (central and perceptual) stages. Now, the order of the two tasks is reversed, i.e., the crucial experimental manipulation is implemented in Task 1. If the manipulation affects the central or perceptual stage of Task 1, the beginning of the Task 2 central stage would be postponed and RT2s should be equally lengthened, i.e., the effect of Task 1 propagates to Task 2 (at least at short SOAs with sufficient temporal overlap between the two tasks). In contrast, if the manipulation affects the motor stage (of Task 1), performance in Task 2 should not be influenced at all, because the motor stage runs in parallel with the Task 2 central stage.

To sum up, the following predictions can be derived within the PRP framework for the RTs of Task 2, the former two relating to the *locus of slack*-logic and the latter two relating to the *effect propagation*-logic:

- If the experimental manipulation is implemented in Task 2, an underadditive interaction between the factor of interest and SOA speaks for a locus in the perceptual stage.
- If the experimental manipulation is implemented in Task 2, additive effects of the factor of interest and SOA speak for a locus in the central or motor stage.
- If the experimental manipulation is implemented in Task 1, a propagation of the effect of interest to Task 2 (especially at short SOAs) speaks for a locus in the perceptual or central stage.
- If the experimental manipulation is implemented in Task 1, the absence of a propagation of the effect of interest to Task 2 speaks for a locus in the motor stage.

1.3. The present experiments

The two available studies reported (1) additive effects when using the locus of slack-logic and (2) effect propagation into Task 2 when using the effect propagation-logic (Kunde et al., 2012; Paelecke & Kunde, 2007). Still, even though they thus favor the view of effect anticipations occurring within the central bottleneck, two critical aspects do not yet allow for drawing definite conclusions. A clarification of these aspects is important because there is also reason to assume a non-central locus of ideomotor effect anticipations. For instance, congruency effects between stimuli and upcoming effects (S–E congruency) arguably rely on anticipative processes just as R–E compatibility effects, but S–E congruency combined underadditively with SOA and thus seems to influence the duration of the pre-central stages in certain settings (Paelecke & Kunde, 2007, Exp. 4 & 5). Additionally, anticipated action effects have been shown to affect movement execution (Kunde, 2003; Kunde, Koch, & Hoffmann, 2004; Pfister, Janczyk, Wirth, Dignath, & Kunde, 2014), which would be in line with a post-central motor-related locus.

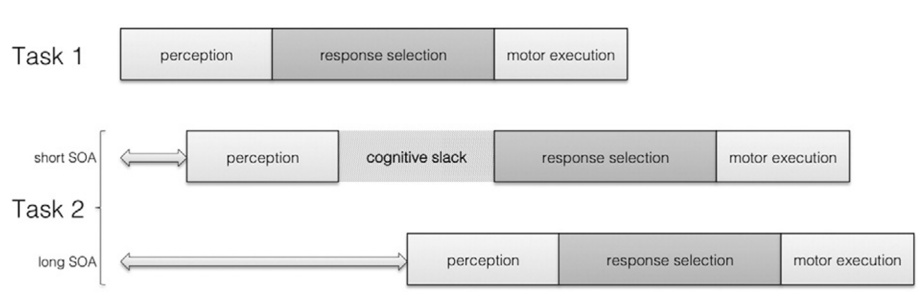

Fig. 1. Illustration of the central bottleneck model (e.g., Pashler, 1994). Because central processes (dark gray) are capacity-limited and cannot overlap in time, in trials with short stimulus onset asynchronies (SOAs, indicated as double arrows), central processing of the second task must wait after its perceptual process has ended. The resulting idle time is called cognitive slack. Responses in the second task therefore take longer with short SOAs compared with long SOAs, and prolonging the perceptual stage of the second task into the cognitive slack does not increase response time in this task.

The first limitation of previous studies on the locus of effect anticipations is a methodological issue relating to the use of blocked designs, and the second limitation relates to the sole reliance on the R–E compatibility effect as an index of anticipations. In the following we describe these issues in more detail and then present four experiments that were designed to overcome these two problems.

1.3.1. Investigating ideomotor effect anticipations

The basic idea of ideomotor theory is that motor actions become associated with, and cognitively represented by, their sensory consequences (Elsner & Hommel, 2001). Sensory consequences are thus the indices that organize an actor's behavioral repertoire, and are used to recruit specific motor actions. Consequently, to select a certain motor action, the action's consequences have to be recollected in the first place. Evidence that supports this idea is often based on RT effects of the compatibility between an action and its following effect, i.e., *R–E compatibility*.

Judging from the literature, most single task studies on R–E compatibility used block-wise manipulations of R–E compatibility (e.g., Kunde, 2001, 2003; Kunde et al., 2004; Kunde, Müsseler, & Heuer, 2007; Pfister & Kunde, 2013; Pfister, Pfeuffer, & Kunde, 2014; Rieger, 2007). This was done to allow participants to straightforwardly predict the upcoming compatible or incompatible action effect. Similarly, such blocked designs were used in the available studies that investigated ideomotor effect anticipations within the PRP paradigm (Kunde et al., 2012; Paelecke & Kunde, 2007). In fact, block-wise manipulations used so far have almost exclusively produced additive effects (e.g., Janczyk, Franz, & Kunde, 2010; Janczyk & Kunde, 2010; Kunde, Landgraf, Paelecke, & Kiesel, 2007; Kunde et al., 2012; Paelecke & Kunde, 2007; Van Selst & Jolicoeur, 1997). And even if an underadditive effect was found in a block-wise manipulation (Karlin & Kestenbaum, 1968), this result was later shown to be an artifact of the employed design (Schubert, 1999) and could possibly be explained by anticipatory response selection processes, i.e., strategic adjustments that allow for bypassing central stages.

There are by now a few single-task studies that manipulated R–E compatibility on a trial-by-trial basis (Ansorge, 2002; Gaschler & Nattkemper, 2012; Pfister, Janczyk, Wirth, Dignath, & Kunde, 2014; Pfister, Kiesel, & Melcher, 2010; Pfister, Melcher, Kiesel, Dechent, & Gruber, 2014; Zwosta, Ruge, & Wolfensteller, 2013), however, such manipulations have not yet been used in a PRP framework. Consequently, in our Experiments 1 and 2 we combined a trial-wise manipulation of R–E compatibility with a PRP setup. Experiment 1 uses the *locus of slack*-logic and manipulated R–E compatibility in Task 2 of a PRP setup; Experiment 2 tests for *effect propagation* by reversing the task order. For the R–E compatibility task we chose a method of continuous spatial responses with the computer mouse. The method of mouse tracking allows not only to reveal an impact of action effects as an extra amount of time, but also as distinct spatial affordances (see Pfister, Janczyk, Wirth, Dignath, & Kunde, 2014; for further uses of this paradigm, see e.g., Dignath, Pfister, Eder, Kiesel, & Kunde 2014b; Wirth, Pfister, Foerster, Huestegge, & Kunde, in press; Wirth, Pfister, & Kunde, 2015).

1.3.2. Further behavioral indications of effect anticipation

Most of the studies on effect anticipations are based on the (spatial) R–E compatibility. If action and effect share features on a common dimension (e.g., a left keypress flashes a left lamp), responses are faster compared to conditions where action and effect features do not match (e.g., a left keypress flashes a right lamp; Shin & Proctor, 2012, effect-type 1 & 2).

Recent evidence suggests, however, that even effects that nominally share no features with the required motor response can affect performance (Shin & Proctor, 2012, effect-type 3). Specifically, when action effects occur consistently with a delay, RTs are delayed compared to conditions in which action effects occur instantaneously (Dignath, Pfister, Eder, Kiesel, & Kunde, 2014a). Thus, not only effect identity is recollected in response generation, but also the time interval that leads to the effect. The increase in RTs when response effects are foreseeably delayed can thus serve as another indicator of effect anticipation.

Therefore, in Experiments 3 and 4, we investigated whether anticipation of action-effect delay equally requires the central bottleneck of response selection. Experiment 3 uses the *locus of slack*-logic by manipulating the effect-delay in Task 2; Experiment 4 tests for *effect propagation* by reversing the task order.

2. Experiment 1

In Experiment 1, we investigated anticipations of spatially compatible and incompatible effects with a trial-wise manipulation of the R–E compatibility by means of a mouse-pointing task (cf. Pfister, Janczyk, Wirth, Dignath, and Kunde (2014)). In a PRP experiment, Task 1 required a tone discrimination, and Task 2 required continuous responses with the computer mouse to move an avatar to the (upper) left or right area of the screen according to a centrally presented stimulus. More precisely, participants moved a virtual avatar to one of two "portals" to attain either a yellow or red cake that was hidden behind one of the portals and displayed only after responding (see Fig. 2A). For one half of the participants, yellow cakes were always hidden behind the right portal and red cakes behind the left portal, and this mapping was reversed for the other half. Importantly there were two different R-E mappings that varied trial-wise. In the R–E compatible condition the portals were switched off (indicated by an 'x' below the portals). Consequently, participants had to move the avatar directly to the portal at which the sought-after cake was going to appear (e.g., to the right portal when looking for a yellow cake). In the R–E incompatible condition, however, the portals were switched on (indicated by check marks below the portals). Now the portals would transport the avatar to the opposite side. Consequently, participants had to move the avatar to the portal opposite to the one where the cake was going to appear (e.g., to the left portal when looking for a yellow cake). In other words, we created conditions in which the spatial mapping between response (mouse movement) and subsequent response effect (occurrence of the cake) was either compatible or incompatible, and – importantly – this mapping varied from trial to trial. Simultaneously, we varied the SOA between this tasks and a preceding binary tone discrimination task. According to the *locus of slack*-logic, an additive effect of SOA and R–E compatibility would point to effect anticipations in the central stage or later. Please note that there was no spatial overlap between the stimuli (which cake was sought for and whether portals were on or off) and responses or response effects. Consequently, influences of S–R or S–E compatibility can be ruled out.

2.1. Method

2.1.1. Participants

Sixteen participants were recruited (10 female; 1 left-handed; mean age = 31.9 years) and received monetary compensation. All participants reported normal vision and hearing and were naïve concerning the hypotheses of the experiment. All participants provided written informed consent prior to the experiment.

2.1.2. Apparatus and stimuli

Stimuli for Task 1 (S1) were two tones (250 vs. 900 Hz, 100 ms) played via headphones. Participants responded with the middle and index finger of their left hand on the "D" and "F" keys of a standard QWERTZ keyboard. The tone-key mapping was counterbalanced across participants.

The experimental setup for Task 2 was similar to a previous single-task study (Pfister, Janczyk, Wirth, Dignath, & Kunde, 2014) and, as in this previous study, stimuli were adapted from the computer game Portal (www.thinkwithportals.com; see Fig. 2). Participants operated a

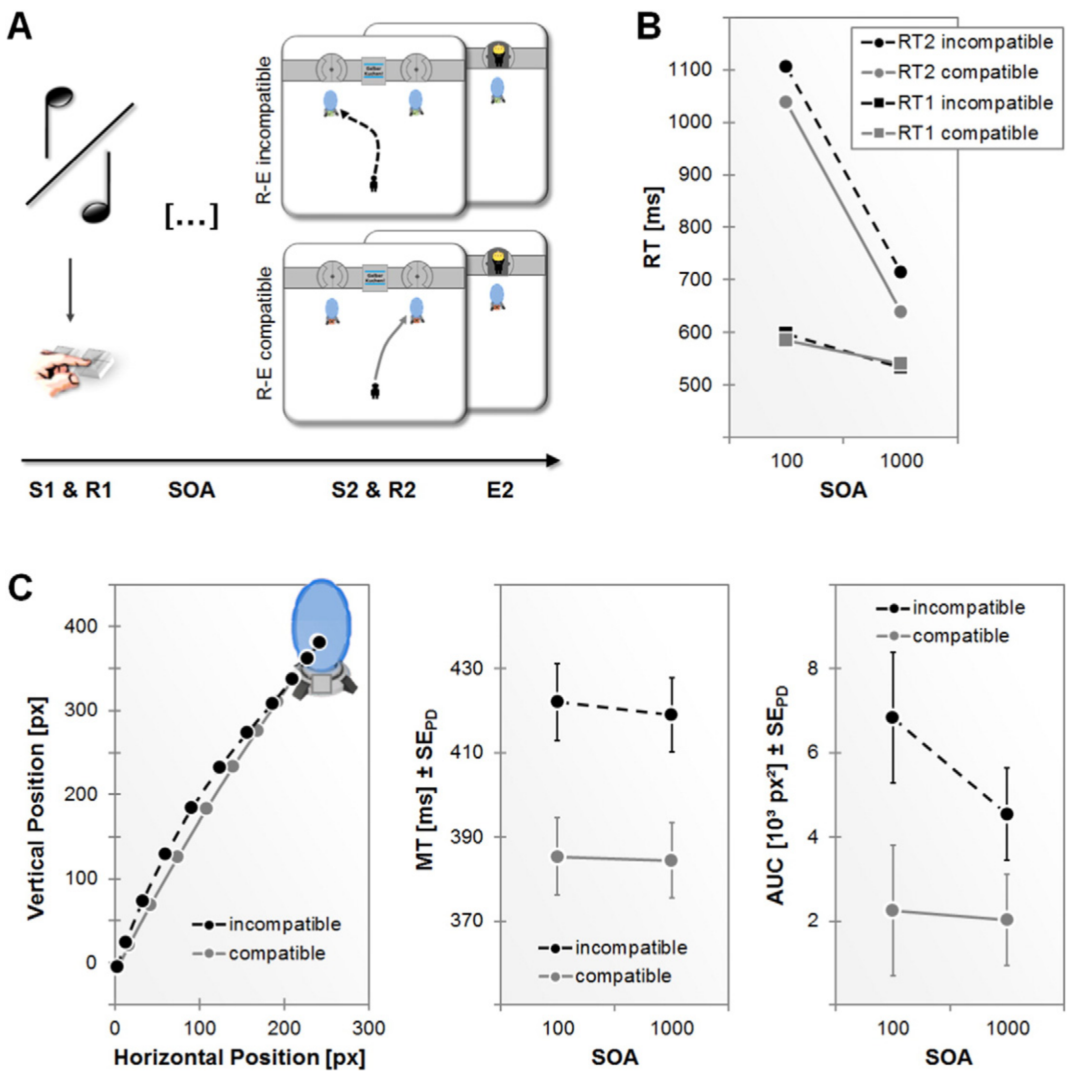

Fig. 2. Design and results of Experiment 1, which used the *locus of slack*-logic with a trial-to-trial manipulation of response–effect (R–E) compatibility in Task 2. (A) Participants responded in two tasks in each trial. Task 1 required a tone discrimination, in which participants classified a tone as high or low by pressing a key with their left hand. Task 2 followed after a stimulus onset asynchrony (SOA) of either 100 ms or 1000 ms. Participants were to attain a cake by moving a virtual avatar from the starting position in the bottom wall (not shown here, as it disappeared when the movement was executed) to one of two portals by using the computer mouse. This avatar was relocated to either the spatially compatible or the spatially incompatible door in the upper wall to receive a complimentary cake. (B) Response times (RTs) for both tasks as a function of SOA and R–E mapping. Error bars were omitted for being illegible at the displayed scale. (C) Time-normalized trajectories of Task 2 and analyses of the trajectory parameters in terms of movement times (MTs) and areas under the curve (AUCs). Error bars represent standard errors of paired differences (Pfister & Janczyk, 2013) that were computed separately for each comparison of R–E compatible and incompatible trials.

standard computer mouse with their right hand and the mouse cursor was substituted for a schematic avatar. The start screen of each trial featured two "walls" spanning horizontally across the screen (height: 1.7 cm) with a distance of 15 cm between the walls. The bottom wall had a single door (2.5 cm × 2.2 cm) in its center that served as the start position. The top wall had two doors (8.5 cm from the left or right screen border, respectively) that contained a virtual cake that participants were told to collect as Task 2 on each trial. These cakes differed in color (yellow vs. red) and the assignment of cake color to door position was constant for each participant (but counterbalanced across participants).

Two portals (1.3 cm × 2.2 cm) were placed 3.5 cm below each door of the top wall. These portals were either switched off (indicated by an 'x' on red ground) or switched on (indicated by a check mark on green ground). The distance between start position and each of the portals was approximately 14 cm. Imperative stimuli (S2) appeared in the center of the top wall (1.9 cm × 2.7 cm) and consisted of the written instructions "Gelber Kuchen!" (German for "Yellow cake!") or "Roter Kuchen!" ("Red cake!").

2.1.3. Instructions and design

Both tasks were instructed separately and a summary screen provided a reminder for all relevant mappings at the end of the instructions. Participants were asked to complete the tasks as quickly and as correctly as possible with Task 1 having to be completed before Task 2 was completed. During instructions of Task 2, participants were given ample time to explore the mapping of door sides to cake colors. Similarly, participants were given time to explore the relation of portal status (on or off) and the door that was reached upon entering one of the portals. That is, portals that were designated to be switched on would relocate the avatar to the door at the other side, whereas portals that were designated to be switched off would not affect the avatars left/right position but rather teleport the avatar to the spatially corresponding door.

Following these instructions, participants completed one practice block and eight experimental blocks of 48 trials each. The trial number resulted from three repetitions of each combination of two possible S1 (high vs. low tone), two SOAs (100 ms vs. 1000 ms), two possible end directions for Task 2 (left vs. right; i.e., yellow vs. red cake), and two possible R–E mappings (compatible vs. incompatible; i.e., portals on vs. portals off). Each block was followed by short break in which participants were informed about their average time to complete a trial and the number of errors in both tasks.

2.1.4. Trial procedure

The trial procedure is illustrated in Fig. 2A. At the beginning of a trial, the avatar spawned below the bottom wall and participants were given time to check whether the portals were switched on or off. To continue, the participants moved the avatar in front of the central door and waited for a dwell time of 500 ms. Then, S1 was played and called for either a left or right key press with the left hand. After an SOA of either 100 ms or 1000 ms, S2 appeared on the screen and called to attain an either red or yellow cake by moving an avatar to either the left or the right portal. The bottom wall disappeared simultaneously with S2 onset, giving way to the avatar's movement. From this point onward, the cursor position was recorded until the end of the trial (effective sampling rates were between 50 and 100 Hz, depending on current CPU load). Participants were to move as quickly as possible to the portal that would teleport the avatar to the correct location. The program waited until a portal was reached, irrespective of whether or not Task 1 had been performed in the meantime.

In case of correct responses in Task 2, the avatar was displayed with a happy face and holding the attained cake, whereas the avatar was displayed with a sad face if the avatar arrived at the wrong location. No further feedback was provided if both tasks had been completed correctly and in the right order. In case of errors in any task, additional written feedback was provided for both tasks in the center of the screen. For Task 1, this message featured the German equivalent of “Tone task: Too early!” for responses prior to S1 onset, “Error!” for wrong key presses, “Too late!” for response omissions or responses after Task 2 had been completed, or “OK!” if Response 1 had been correct but an error occurred in Task 2. Errors in Task 2 were fed back via “Cake task: Too early!” if the avatar had left the start area before S2 onset, “Error!” for movements to the wrong portal, or “OK!” if Response 2 had been correct but an error occured in Task 1. Feedback stayed on screen for 2000 ms, and mouse movements did no longer affect the display. Finally, the screen was cleared and the next trial started after 1000 ms.

2.1.5. Data treatment

RT1 was defined as the time from S1 onset to the key press, whereas RT2 was measured from S2 onset until the cursor's y-coordinate first exceeded the coordinates of the borders of the (now disappeared) bottom wall. Movement time (MT) in Task 2 was measured from this point until the cursor hit the borders of a portal. Trajectory data for each cursor movement was analyzed via custom MATLAB scripts. Cursor x- and y-coordinates were first transformed to a coordinate system with origin at the starting position. Movements to the left were mirrored at the vertical axis to allow for aggregation across both movement directions. Then, cursor coordinates were time-normalized to 101 steps via linear interpolation and areas under the curve (AUCs) were computed as the discrete integral between actual and optimal trajectory on the time-normalized data (with optimal trajectory being defined as a straight line from start to end coordinates). Positive values indicated deviations towards the spatially opposite portal, and negative values indicated deviations away from the spatially opposite portal.

2.2. Results

For all analyses we excluded trials with early responses (Task 1: 0.1%, Task 2: 0.9%), errors (Task 1: 2.0%, Task 2: 2.7%), trials following errors, trials with inter-response intervals less than 50 ms, response omissions in Task 1 (0.3%) and collisions with the upper wall in Task 2 (0.7%). The remaining trials were screened for outliers and we removed trials in which any measure deviated more than 2.5 standard deviations from the corresponding cell mean, computed separately for each participant and experimental condition (9.1%). Overall, 20.3% of all trials were removed. The remaining data were analyzed via 2 × 2 repeated-measures ANOVAs with the factors SOA (100 ms vs. 1000 ms) and R–E mapping (compatible vs. incompatible), separately for each dependent measure.

2.2.1. RTs and error rates

The RT results for both tasks are displayed in Fig. 2B (see Table A1 in the Appendix for detailed descriptive statistics). The analysis of Task 1 yielded a significant main effect of SOA, $F(1,15) = 11.28$, $p = .004$, $\eta_p^2 = .43$, driven by slightly longer RT1s at the short SOA as compared to the long SOA. The main effect of R–E mapping was not significant ($F < 1$), whereas the interaction showed a non-significant trend, $F(1,15) = 3.61$, $p = .077$, $\eta_p^2 = .19$.

The analysis of Task 2 yielded a profound PRP effect as indicated by longer RT2s at the short compared to the long SOA, $F(1,15) = 130.61$, $p < .001$, $\eta_p^2 = .90$. A significant main effect of R–E compatibility further indicated that RT2s were longer in the R–E incompatible condition than in the R–E compatible condition, $F(1,15) = 33.64$, $p < .001$, $\eta_p^2 = .69$. Most importantly, the effects of SOA and R–E compatibility were additive as indicated by a non-significant interaction ($F < 1$, BF = 3.37 in favor of the null-hypothesis of no interaction).[1]

Analyses of the corresponding error rates (see Table A1 for descriptive statistics) confirmed that these effects were not undermined by speed–accuracy trade-offs. For Task 1, we found a non-significant trend for the main effect of SOA, $F(1,15) = 3.17$, $p = .095$, $\eta_p^2 = .17$, whereas the main effect of R–E mapping, $F(1,15) = 1.08$, $p = .315$, $\eta_p^2 = .07$, and the interaction, $F(1,15) = 2.47$, $p = .137$, $\eta_p^2 = .14$, did not approach significance. For Task 2, significant main effects of SOA, $F(1,15) = 4.99$, $p = .041$, $\eta_p^2 = .25$, and R–E mapping, $F(1,15) = 8.53$, $p = .011$, $\eta_p^2 = .36$, were driven by higher error rates for the short compared to the long SOA and for the incompatible rather than the compatible R–E condition, respectively. This difference was larger at the short SOA than at the long SOA giving rise to a significant interaction, $F(1,15) = 10.49$, $p = .006$, $\eta_p^2 = .41$.

2.2.2. Trajectory data

Additional analyses examined the trajectory data of Task 2. Mean trajectories as a function of R–E mapping are plotted in Fig. 2C (left panel), together with the results for MTs and AUCs (middle and right panel; see also Table A2 in the Appendix for descriptive statistics). These analyses suggest a strong impact of R–E mapping on MTs, $F(1,15) = 19.54$, $p < .001$, $\eta_p^2 = .57$, with longer MTs in the incompatible than in the compatible condition. MTs were not affected by SOA and the interaction did not approach significance either ($Fs < 1$).

A significant effect of R–E mapping also emerged for AUCs, $F(1,15) = 8.12$, $p = .012$, $\eta_p^2 = .35$, whereas the main effect of SOA failed to reach significance again, $F(1,15) = 1.47$, $p = .245$, $\eta_p^2 = .09$. In contrast to the MT results, however, a marginally significant interaction indicated that AUCs were especially large in the incompatible condition at short SOAs, $F(1,15) = 4.22$, $p = .058$, $\eta_p^2 = .22$.

2.3. Discussion

Experiment 1 employed a trial-wise manipulation of R–E compatibility in Task 2 of a PRP experiment. The results were clear-cut: Responding in Task 2 took consistently longer for the R–E incompatible

[1] The present sample size of 16 participants might cause concerns about whether the absence of an interaction might be due to a lack of statistical power. We therefore increased the sample size post-hoc to $n = 32$ participants and still found a clearly additive pattern. There was still a sizeable effect of R–E mapping for RT2 (compatible: 907 ms, incompatible: 856 ms), $F(1,31) = 35.44$, $p < .001$, $\eta_p^2 = .53$, but no sign of an interaction with SOA, $F(1,31) < 0.01$, $p = .964$, $\eta_p^2 < .01$. An additional analysis of the Bayes-Factors for the interaction yielded substantial evidence in favor of the null-hypothesis, BF = 5.29.

trials as compared to the R–E compatible trials and this impact of R–E compatibility was additive to the effect of SOA. According to the *locus of slack*-logic, this pattern of results indicates that ideomotor effect anticipations (as indicated by R–E compatibility effects) do indeed happen within the central or motor stage. Our results therefore extend previous results obtained with block-wise manipulations of R–E compatibility (Kunde et al., 2012; Paelecke & Kunde, 2007) to trial-wise manipulations and suggest that previous results were not a methodological artifact due to block-wise designs.

It is important to note that, in the present R-E compatibility design, stimulus features alone could not have driven the results. If we neglected the action effects here, we would simply see that certain combinations of stimulus features (portal status and cake color) are easier than others (even though there is no reasonable justification to assume so), but these combinations only become meaningful when they are viewed from the perspective of the action effect that these combinations will trigger: some combinations produce effects that are spatially compatible to the response and consequently are easier to perform than those combinations that will ultimately produce incompatible action effects. Also, the trajectory data shows that movements are typically attracted to the location where the action effect will later appear, even though the effect was not present at the time of movement execution. Therefore, we feel that it is safe to say that action effects here play a crucial role in both, the response selection and execution.

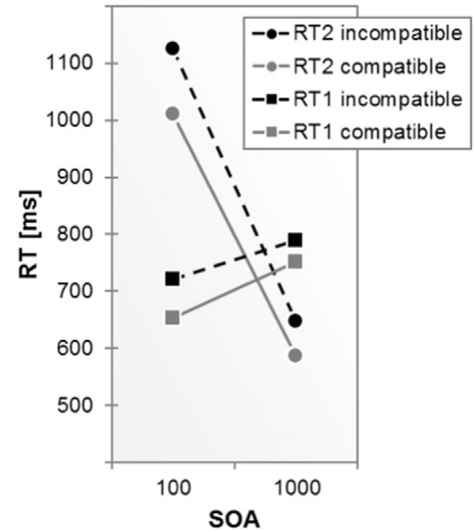

Fig. 3. Response times (RT) for both tasks of Experiment 2 (using the *effect propagation*-logic) as a function of response–effect (R–E) compatibility and stimulus onset asynchrony (SOA). Task 1 now was the R–E compatibility task and the tone discrimination task was now implemented as Task 2. Error bars were omitted for being illegible at the displayed scale.

3. Experiment 2

In Experiment 2, we tested for *effect propagation* of the R–E compatibility effect to further differentiate the motor stage from earlier stages as possible loci of the effect. We therefore reversed the task order and implemented the crucial manipulation of R–E compatibility in Task 1. Observing the R–E compatibility effect to propagate to the following tone discrimination task (especially at short SOAs) would exclude the motor stage as the locus of ideomotor effect anticipations.

3.1. Method

Sixteen new participants were recruited (13 female; all right-handed; mean age = 26.6 years) and received monetary compensation. They fulfilled the same criteria as in Experiment 1.

Stimuli, apparatus, and procedure were exactly as in Experiment 1 except that the task order was reversed: Participants were first prompted to collect either the red or the yellow cake (Task 1), and the tone stimulus for Task 2 set on after an SOA of either 100 ms or 1000 ms. Participants had a response window of 2000 ms for Task 2 whereas the program again waited until Task 1 had been completed in any case.

3.2. Results

We again removed trials with premature responses (Task 1: 1.3%, Task 2: none), errors (Task 1: 3.5%, Task 2: 2.2%), trials following these errors, trials with inter-response intervals less than 50 ms, collisions with the wall in Task 1 (0.6%), and response omissions in Task 2 (0.1%). Further outliers were removed as in Experiment 1 (7.5%). Overall, 22.2% of all trials were removed.

3.2.1. RTs and error rates

The RT results for both tasks are plotted in Fig. 3 (see also Table A1 in the Appendix for descriptive statistics). The analysis of RT1 yielded a marginally significant effect of SOA, $F(1,15) = 3.90$, $p = .067$, $\eta_p^2 = .21$, and, importantly, a significant main effect of R–E mapping, $F(1,15) = 5.74$, $p = .030$, $\eta_p^2 = .28$, indicating that RT1 were longer in the R–E incompatible condition than in the R–E compatible condition. The interaction also approached significance, $F(1,15) = 3.92$, $p = .066$, $\eta_p^2 = .20$, driven by a slightly larger effect of R–E mapping for the short compared to the long SOA.

Most importantly, R–E mapping also had a significant effect on RT2, $F(1,15) = 12.84$, $p = .003$, $\eta_p^2 = .46$, with longer RTs for R–E incompatible trials than for R–E compatible trials. Furthermore, a PRP effect was evident in terms of a main effect of SOA, $F(1,15) = 84.05$, $p < .001$, $\eta_p^2 = .85$, whereas the interaction failed to reach significance, $F(1,15) = 2.78$, $p = .116$, $\eta_p^2 = .16$.

Analyses of the error rates (see Table A1) confirmed that none of the RT effects was due to a speed–accuracy trade-off, and no effect approached significance for the error data of Task 1, $ps \geq .290$. For Task 2, errors tended to be more frequent in the incompatible R–E condition than in the compatible R–E condition, $F(1,15) = 3.41$, $p = .085$, $\eta_p^2 = .19$, whereas neither the main effect of SOA ($F < 1$), nor the interaction, $F(1,15) = 2.67$, $p = .123$, $\eta_p^2 = .15$, were significant.

3.2.2. Trajectory data

Preliminary screening of the trajectory data (Table A2 in the Appendix) indicated that participants did not perform a single, smooth movement as instructed. Rather, most participants started with a short initial movement, stopped for a certain period of time, and resumed the movement only after having completed Task 2. More precisely, extended stops for a continuous duration of 10 normalized time-steps within the first half of the movement occurred in 20.3% of the trials[2] whereas such stops virtually did not occur in Experiment 1 (0.8%), $t(30) = 2.24$, $p = .032$, $d = 0.79$. Trajectory data of Task 1 are thus difficult to interpret, and we only include the corresponding statistics for the sake of completeness.

MTs were longer at the long SOA as compared to the short SOA, $F(1,15) = 18.46$, $p < .001$, $\eta_p^2 = .55$, and were similarly longer in R–E incompatible than in R–E compatible trials, $F(1,15) = 7.10$, $p = .018$,

[2] To ensure that these full stops did not contaminate the RT results reported above, we re-analyzed the RTs of both tasks after removing all stop trials. For this re-analysis, two participants had to be removed for an insufficient number of trials for a design cell (<10). Analysis of RT1 yielded a significant effect of R–E mapping, $F(1, 13) = 6.09$, $p = .028$, $\eta_p^2 = .32$, and a marginally significant effect of SOA, $F(1, 13) = 4.34$, $p = .058$, $\eta_p^2 = .25$. Moreover, the R–E mapping effect was larger with a short than with a long SOA, $F(1, 13) = 6.85$, $p = .021$, $\eta_p^2 = .34$. Importantly, the R–E mapping effect was still significant for RT2, $F(1, 13) = 5.74$, $p = .028$, $\eta_p^2 = .31$, along with a significant effect of SOA, $F(1, 13) = 122.54$, $p < .001$, $\eta_p^2 = .90$, and a now significant interaction between the two factors, indicating a larger R–E mapping effect at the short compared to the long SOA, $F(1, 13) = 5.64$, $p = .034$, $\eta_p^2 = .30$. Overall, the experimental manipulation in Task 1 still propagated to Task 2, even when trials where the subsequent movement had not been fully planned (and that consequently result in a full stop) were removed.

$\eta_p^2 = .32$. The interaction was not significant, $F(1,15) = 1.10$, $p = .311$, $\eta_p^2 = .07$. AUCs, by contrast, were not affected by SOA, $F(1,15) = 1.83$, $p = .196$, $\eta_p^2 = .11$, but were again larger in R–E incompatible than in R–E compatible trials, $F(1,15) = 5.91$, $p = .028$, $\eta_p^2 = .28$. The interaction was not significant again ($F < 1$).

3.3. Discussion

In Experiment 2, we implemented a trial-wise manipulation of R–E compatibility in Task 1 of a PRP experiment. This setup not only showed a reliable R–E compatibility effect for this task, but also showed this effect to propagate to Task 2. According to the *effect propagation*-logic, this pattern of results excludes the motor stage as the source of the R–E compatibility effect. Together with the results of Experiment 1, we conclude that effect anticipations – as measured via R–E compatibility effects – do indeed coincide with the central stage of response selection, even when controlling for possible methodological artifacts resulting from the block-wise presentation, that was used in earlier studies on this topic (Kunde et al., 2012; Paelecke & Kunde, 2007).

4. Experiment 3

As described in the introduction, previous studies used R–E compatibility as the sole indicator to investigate the locus of effect anticipations (Kunde et al., 2012; Paelecke & Kunde, 2007), which limits their generalizability (Shin & Proctor, 2012, effect-type 1 & 2). Recent evidence, however, suggests that motor actions are also affected by subsequent effects when there is no obvious overlap between actions and effects. Specifically, immediate action effects speed up responses compared to action effects that occur foreseeably delayed (Dignath et al., 2014a; Kiesel & Hoffmann, 2004; Shin & Proctor, 2012, effect-type 3). It seems as if not only the effect identity is recollected for response production, but also the time interval that leads to the effect.

To study effect anticipations that do not revolve around the compatibility of responses and effects, but rather include the time interval in between them, we investigated whether anticipations of the action-effect delay equally require the central bottleneck of response selection. Similar to Experiment 1, Experiment 3 therefore used the *locus of slack*-logic, with the action-effect delay being manipulated in Task 2.

Task 1 was again a tone discrimination task, whereas Task 2 now required left or right key press responses to a centrally presented visual stimulus. The effect to the second response was predictably delayed either for a long or a short amount of time, consequently the delay varied trial-wise (R–E delay). As the delay between the response and the effect onset was not specifically needed to ensure an adequate task performance, the R–E delay was nominally and technically task irrelevant. If the assumption of effect anticipations in the central stage still holds true for task-irrelevant features (Shin & Proctor, 2012, effect-type 3), we can expect an additive effect of the SOA and the R–E delay.

4.1. Method

4.1.1. Participants

Sixteen new participants were recruited (12 female; 1 left-handed; mean age = 21.0 years) and received course credit. They fulfilled the same criteria as in Experiments 1 and 2.

4.1.2. Apparatus and stimuli

Task 1 was the same tone discrimination task as used before. In Task 2, participants again saw a screen containing an avatar and two portals. These portals, however, were placed in the lower half of the screen and the avatar was placed equidistantly from both portals (see Fig. 4A). Mouse movements no longer affected the avatar, but instead participants were to press the left or the right mouse button as the response. Two walls (height: 1.7 cm) subdivided the screen at 4.5 cm from the top and bottom, respectively. The top wall contained a single door in its horizontal center. The picture of a red or yellow cake appeared in this door as S2. Participants were asked to press the left or the right mouse button according to the S2 cake color to enter either the left or the right portal and be teleported to the door. The color-response mapping was counterbalanced across participants.

4.1.3. Instructions and design

Participants were instructed that one portal would operate slowly whereas the other one would operate quickly. The slow and the fast portal were marked with check marks on either orange or blue ground at the portal's base (with color-speed assignment being counterbalanced across participants), and the position of the portals was constant for each participant. The fast portal teleported the avatar to the door after 50 ms, whereas the slow portal took 2000 ms to do so. The successful teleport was further accompanied by a "*swish*" sound that was played via headphones to further emphasize the action effect.

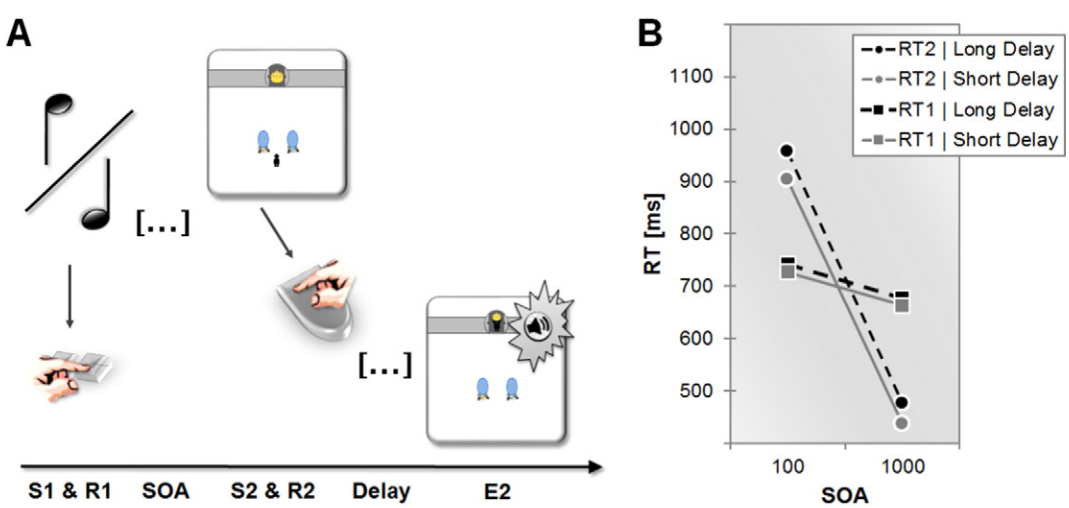

Fig. 4. Design and results of Experiment 3 (using the *locus of slack*-logic). (A) Participants responded in two tasks in each trial. Task 1 required a tone discrimination in which participants classified a tone as high or low by pressing a key with their left hand. Task 2 followed after a stimulus onset asynchrony (SOA) of either 100 ms or 1000 ms. Participants were to press the left or right mouse button to enter either a slow or a fast portal. The avatar was then teleported with a delay of either 50 ms or 2000 ms to the door in the upper center. (B) Response times (RTs) for both tasks as a function of SOA and response–effect delay. Error bars were omitted for being illegible at the displayed scale.

Participants completed one training block and eight experimental blocks of 48 trials each. These trials corresponded to six repetitions of two possible S1 (high vs. low tone), two SOAs (100 ms vs. 1000 ms), and two S2 (red vs. yellow cake, i.e., 50 ms delay vs. 2000 ms delay).

4.1.4. Trial procedure

Trials started with the avatar being placed next to the two portals (see Fig. 4A), the door in the upper center being closed and S1 being played. Following the SOA, the door opened and showed either a red or a yellow cake as S2 and the program waited until a response was made for this task. The avatar disappeared immediately after a response had been made for Task 2 and reappeared in the door after either 50 ms or 2000 ms (depending on which response had been made). In correct trials, the avatar was displayed with a happy face holding the attained cake, whereas it was shown with a sad face in case of wrong responses. Error feedback was provided as in Experiments 1 and 2.

4.2. Results

As for the preceding experiments, we excluded trials with premature responses (Task 1: 0.1%, Task 2: 0.2%), errors (Task 1: 2.2%, Task 2: 3.0%), trials following errors, trials with inter-response intervals less than 50 ms, and response omissions in Task 1 (0.2%). Outliers were removed if either RT1 or RT2 deviated more than 2.5 standard deviations from the corresponding cell mean, computed separately for each participant and experimental condition (4.0%). Overall, 19.4% of all trials were removed. Analyses were done by means of 2 × 2 repeated measures ANOVAs with the factors SOA (100 ms vs. 1000 ms) and R–E delay in Task 2 (50 ms vs. 2000 ms).

The data of both tasks are plotted in Fig. 4B (see also Table A3 in the Appendix for descriptive statistics). RT1 was generally unaffected by the experimental manipulations with neither main effect, $ps \geq .137$, nor the interaction reaching significance ($F < 1$). RT2s were longer at the short as compared to the long SOA, $F(1,15) = 337.27$, $p < .001$, $\eta_p^2 = .96$, and they were longer with the long compared to the short R–E delay, $F(1,15) = 17.09$, $p < .001$, $\eta_p^2 = .53$. Most importantly, these effects were additive as suggested by a non-significant interaction ($F < 1$, BF = 3.12 in favor of the null-hypothesis).

The error rates of Task 1 yielded neither a significant effect of SOA, $F(1,15) = 3.40$, $p = .085$, $\eta_p^2 = .18$, nor of R–E delay, $F(1,15) = 2.10$, $p = .168$, $\eta_p^2 = .12$. The interaction was not significant either, $F(1,15) = 1.80$, $p = .200$, $\eta_p^2 = .11$. For Task 2, there was a significant main effect of R–E delay, $F(1,15) = 7.02$, $p = .018$, $\eta_p^2 = .32$, with higher error rates with the long than with the short R–E delay. Neither of the remaining effects approached significance ($Fs < 1$).

4.3. Discussion

Experiment 3 varied the R–E delay in Task 2 of a PRP experiment on a trial-wise basis. Responding in Task 2 was consistently slower in trials with long R–E delays as compared to those with short R–E delays. Most importantly, this consistent impact of R–E delay was additive to the effect of SOA. According to the *locus of slack*-logic, this pattern of results indicates that anticipations of predictable R–E delays affect the central or motor stage, even though these effect features do not share spatial features with the response as in Experiment 1 and were not necessary for the completion of the task (Shin & Proctor, 2012, effect-type 3).

5. Experiment 4

In Experiment 4, we complemented Experiment 3 by testing for *effect propagation* of the R–E delay effect. Thus, the R–E delay manipulation was now realized in Task 1, and a propagation of the R–E delay effect to Task 2 performance would speak for effect anticipations prior to the motor stage.

5.1. Method

Sixteen new participants were recruited (13 female; all right-handed; mean age = 21.5 years) and received course credit. They fulfilled the same criteria as in the preceding experiments.

Stimuli, apparatus, and procedure were exactly as in Experiment 3 except that the task order was reversed: Participants were first prompted to respond to the color of the red or yellow cake that had to be collected (Task 1), and the tone stimulus for Task 2 occurred after an SOA of either 100 ms or 1000 ms. Participants had a response window of 2000 ms for Task 2 whereas the program again waited until Task 1 had been completed in any case.

5.2. Results

Trials with premature responses (Task 1: 0.1%, Task 2: 0.6%), errors (Task 1: 2.3%, Task 2: 5.4%), trials following errors, trials with inter-response intervals less than 50 ms, and response omissions in Task 2 (0.9%), as well as were outliers (4.3%), were removed. Overall, 19.6% of all trials were removed.

The RT results for both tasks are plotted in Fig. 5. RT1 was unaffected by SOA ($F < 1$), and also the main effect of R–E delay failed to reach significance, $F(1,15) = 2.52$, $p = .134$, $\eta_p^2 = .14$. The interaction was not significant either, $F(1,15) = 1.79$, $p = .200$, $\eta_p^2 = .11$. For RT2, there was a significant main effect of SOA, $F(1,15) = 262.49$, $p < .001$, $\eta_p^2 = .95$, driven by longer RTs with the short SOA compared to the long SOA. Furthermore, there was a significant main effect of R–E delay, $F(1,15) = 9.15$, $p = .009$, $\eta_p^2 = .38$, indicating longer RT2s for the long delay as compared to the short delay. The interaction was not significant ($F < 1$). No effect approached significance in the analyses of the error rates ($ps > .285$), except for the main effect of SOA in Task 1, $F(1,15) = 9.88$, $p = .007$, $\eta_p^2 = .40$.

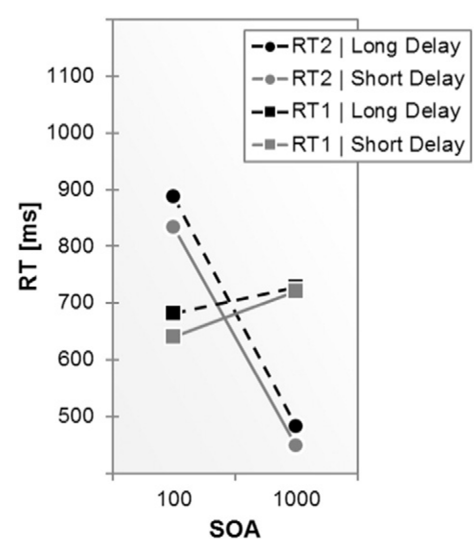

Fig. 5. Response times (RT) for both tasks of Experiment 4 (using the *effect propagation*-logic) as a function of stimulus onset asynchrony (SOA) and response–effect (R–E) delay. Task 1 now was the portal task that included a short or long R–E delay whereas the tone discrimination task was implemented as Task 2. Error bars were omitted for being illegible at the displayed scale.

5.3. Discussion

In Experiment 4 we manipulated the R–E delay in Task 1 of a PRP experiment. We found descriptively longer RTs in Task 1 with long compared to short R–E delay, and this effect propagated to Task 2.[3] According to the *effect propagation*-logic, the propagation of the Task 1 manipulation into Task 2 RTs indicates the R–E delay effect to influence the central or an earlier stage. Together with the results of Experiment 3, we can conclude that the R–E delay manipulation does indeed affect the central stage of response selection, even though it employed effects that do not share common features with the response.

6. General discussion

With the present set of PRP experiments, we investigated within which stage of information processing effect anticipations occur. To do so, we manipulated the (spatial) compatibility (Experiments 1 & 2) and the delay (Experiments 3 & 4) between a response and its effect.

First, we addressed a major methodological confound of previous research: R–E compatibility was usually manipulated block-wise (Kunde et al., 2012; Paelecke & Kunde, 2007). Following recent studies that employed trial-wise manipulations of R–E compatibility (Ansorge, 2002; Gaschler & Nattkemper, 2012; Pfister, Janczyk, Gressmann, Fournier, & Kunde, 2014; Pfister et al., 2010; Zwosta et al., 2013), we ruled out methodological issues that could arise with block-wise manipulations.

In Experiment 1, we employed the *locus of slack*-logic and manipulated spatial R–E compatibility in Task 2. The additive effect of SOA and R–E compatibility pointed to effect anticipations in the central or later stage. Experiment 2 tested for *effect propagation* by reversing the task order and the effect found in Experiment 1 propagated to Task 2, pointing to effect anticipations prior to the motor stage. Taken together, these results indicate that effect anticipations take place in the central stage of information processing and therefore require the central bottleneck, which is typically associated with “response selection” in sensorimotor models. Thus, we were able to replicate the results of previous research (Kunde et al., 2012; Paelecke & Kunde, 2007) even with a trial-wise variation of spatial R–E compatibility. The use of continuous mouse movement responses further revealed that response execution drifted towards the location of anticipated action consequences. Note that the observation that R–E compatibility affects RTs at a stage before response execution does not contradict that R–E compatibility also affects spatial parameters of response execution. The PRP methodology is only apt to capture RT effects. It might be that the spatial distortions of movement execution reflect what had been prepared prior to response initiation (and affects RT as well), or, what seems equally tenable, that codes of action effects remain active after response initiation and affect response execution independently of RTs. This issue deserves further research.

Secondly, we investigated the impact of effect manipulations for effects that, in contrast to sharing common features with the required response (Shin & Proctor, 2012, effect-types 1 & 2), are non-overlapping with features of the required responses (effect-type 3). We did so by manipulating the R–E delay in Task 2 and observed an additive effect of SOA and R–E delay in Experiment 3. Experiment 4 finally yielded *effect propagation* when reversing the task order. Taken together, these results indicate that the effect of R–E delay also has a source in the central stage of information processing, much like the R–E compatibility effect investigated in Experiments 1 and 2.

Assuming that the R–E delay manipulation used in Experiments 3 and 4 also affected effect features that were anticipated for response selection (similar to what is assumed for the more typical R–E compatibility manipulations), we can conclude that anticipation of all types of effect features are processed similarly, underlie the same mechanism, and appear to coincide with what sensorimotor models call response selection (see also Janczyk and Kunde (2014); Janczyk, Pfister, Hommel, and Kunde (2014); Kunde et al. (2012)).

However, there are admittedly other reasons that may have produced the RT effect depending on R–E delay. One obvious point is that the overall trial duration was longer in the case of the long R–E delay. This experience may have caused less motivation on these trials and therefore have increased RTs. Of course, this somehow implies anticipating the long inter-trial interval, but in this case it is difficult to reconcile this anticipatory process with response selection processes per se. Thus, although suggestive, future studies are required to disentangle various explanations for the effect of R–E delays.

Another observation that we do not want to leave unnoticed is that, in the experiments that used the *effect propagation*-logic (Experiments 2 & 4), RT effects of the R–E manipulation were larger for Task 2 even though the manipulation was implemented in Task 1.[4] The effects therefore did not simply propagate, but they seem to *over*propagate. Traditional PRP models (e.g., Pashler, 1994) do not account for such an increased effect, and we can therefore only speculate about possible mechanisms behind this effect. We presume that the employed mouse movement tasks call for an additional cognitive process during and after the response; one that is in charge of continued effect monitoring. If we assume that this process draws on central resources (e.g., Welford, 1952), this might explain this pattern of results. When the tone discrimination task is implemented as Task 1, all available resources can be allocated towards it, but when implemented as Task 2, the effect monitoring process that was triggered after the portal task (i.e., Task 1) still requires some of the available resources, cutting from the resources that can be provided for Task 2, and consequently impairing the ability to respond fast and accurately specifically in conditions of an anticipatory mismatch. This speculation definitely calls for further research. A slightly problematic aspect of the Experiment 2 and 4 data relates to the non-significant interaction of SOA and R–E compatibility or R–E delay. Against the background of the central bottleneck model, the propagation should diminish with longer SOAs, leading to an overadditive interaction (this was the case in Kunde et al. (2012), Exp. 3). We do not know exactly the reason for the absence of this interaction, but please note that the descriptive pattern goes clearly into the right direction. It might be that with the mouse movement responses, an SOA even longer than our long SOA of 1000 ms would be required to avoid any effect propagation from Task 1 into Task 2.

To conclude, the present study presents an important step towards reconciling sensorimotor and ideomotor approaches of action control: Effect anticipations as proposed by ideomotor models as the critical mechanism for initiating bodily movements, coincide with what sensorimotor stage models describe as central processes of response selection.

Acknowledgment

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[3] It was somewhat surprising that the effect of R–E delay did affect RT 1 descriptively, but not significantly. We conjecture though, that this was a matter of insufficient power. When we increased the sample size post-hoc to $n = 32$ participants, the effect of R–E delay was significant for RT1 (immediate: 639 ms, delayed: 665 ms), $F(1,31) = 4.80$, $p = .036$, $\eta_p^2 = .13$, and still propagated to RT2, (immediate: 640 ms, delayed 671 ms), $F(1,31) = 7.91$, $p = .008$, $\eta_p^2 = .20$.

[4] Comparing the R–E compatibility effects of Experiment 2 yielded a significantly stronger effect for Task 2 (the tone discrimination task; $\Delta RT2 = 88$ ms) than for Task 1 ($\Delta RT1 = 53$ ms), $t(15) = 2.14$, $p = .049$, $d = 0.54$. Descriptively, a similar picture emerged for the effect of R–E delay in Experiment 4 ($\Delta RT1 = 24$ ms, $\Delta RT2 = 44$ ms), even though the corresponding difference in effects did not reach significance, $t(15) = 1.71$, $p = .108$, $d = 0.43$.

Appendix A

Table A1
Response times (RTs) and percentages error (PEs) for both tasks of Experiments 1 and 2. Note that Experiment 1 featured the tone discrimination task as Task 1 and the portal task (including the manipulation of R–E compatibility) as Task 2 whereas task order was reversed for Experiment 2.

		RT1 [ms]		RT2 [ms]		PE1 [%]		PE2 [%]	
		SOA		SOA		SOA		SOA	
Experiment	R–E mapping	100	1000	100	1000	100	1000	100	1000
Exp. 1	Incompatible	599	534	1106	715	1.83	1.82	5.26	2.89
	Compatible	585	541	1038	638	2.76	1.50	1.39	1.34
Exp. 2	Incompatible	721	790	1126	648	3.98	3.17	2.67	2.02
	Compatible	653	752	1012	587	2.65	3.17	1.31	1.31

Table A2
Trajectory results for movement times (MTs) and areas under the curve (AUCs) of the portal task in Experiments 1 and 2.

		MT [ms]		AUC [px^2]	
		SOA		SOA	
Experiment	R–E mapping	100	1000	100	1000
Exp. 1	Incompatible	422	419	6832	4538
	Compatible	385	384	2251	2019
Exp. 2	Incompatible	969	1248	6042	5290
	Compatible	892	1194	5294	4056

Table A3
Response times (RTs) and percentage errors (PEs) for both tasks of Experiments 3 and 4. Note that Experiment 3 featured the tone discrimination task as Task 1 and the portal task (including the manipulation of R–E delay) as Task 2 whereas task order was reversed for Experiment 2.

		RT1 [ms]		RT2 [ms]		PE1 [%]		PE2 [%]	
		SOA		SOA		SOA		SOA	
Experiment	R–E delay	100	1000	100	1000	100	1000	100	1000
Exp. 3	2000	741	678	958	477	2.62	2.42	3.14	3.34
	50	727	664	903	437	2.55	1.37	2.48	2.52
Exp. 4	2000	681	728	887	483	3.45	1.17	5.89	4.76
	50	640	721	833	449	3.00	1.76	5.68	5.86

References

Ansorge, U. (2002). Spatial intention–response compatibility. *Acta Psychologica*, *109*, 285–299.

Badets, A., Koch, I., & Toussaint, L. (2013). The role of an ideomotor mechanism in number processing. *Experimental Psychology*, *60*, 34–43.

Chen, J., & Proctor, R. W. (2013). Response–effect compatibility defines the natural scrolling direction. *Human Factors*, *55*, 1112–1129.

Dignath, D., Pfister, R., Eder, A., Kiesel, A., & Kunde, W. (2014a). Representing the hyphen in bi-directional action–effect associations: Automatic integration of time intervals into cognitive action structures. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *40*(6), 1701–1712.

Dignath, D., Pfister, R., Eder, A. B., Kiesel, A., & Kunde, W. (2014b). Something in the way she moves—Movement trajectories reveal dynamics of self-control. *Psychonomic Bulletin & Review*, *21*(3), 809–816.

Elsner, B., & Hommel, B. (2001). Effect anticipation and action control. *Journal of Experimental Psychology: Human Perception and Performance*, *27*(1), 229–240.

Gaschler, R., & Nattkemper, D. (2012). Instructed task demands and utilization of action effect anticipation. *Frontiers in Psychology*, *3*, 578.

Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: With special reference to the ideomotor mechanism. *Psychological Review*, *77*(2), 73–97.

Hoffmann, J. (1993). *Vorhersage und Erkenntnis: Die Funktion von Antizipationen in der menschlichen Verhaltenssteuerung und Wahrnehmung [Anticipation and cognition: The function of anticipations in human behavioral control and perception]*. Göttingen: Hogrefe.

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences*, *24*, 849–937.

James, W. (1890). *The principles of psychology*, *Vol. 1–2*, Cambridge, MA: Harvard University Press.

Janczyk, M. (2013). Level 2 perspective taking entails two processes: Evidence from PRP experiments. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*, 1878–1887.

Janczyk, M., Augst, S., & Kunde, W. (2014). The locus of the emotional Stroop effect. A study with the PRP paradigm. *Acta Psychologica*, *151*, 8–15.

Janczyk, M., Dambacher, M., Bieleke, M., & Gollwitzer, P. M. (2015). The benefit of no choice: Goal-directed plans enhance perceptual processing. *Psychological Research*, *79*, 206–220.

Janczyk, M., Franz, V. H., & Kunde, W. (2010). Grasping for parsimony: Do some motor actions escape dorsal processing? *Neuropsychologia*, *48*, 3405–3415.

Janczyk, M., & Kunde, W. (2010). Does dorsal processing require central capacity? More evidence from the PRP paradigm. *Experimental Brain Research*, *203*, 89–100.

Janczyk, M., & Kunde, W. (2014). The role of effect grouping in free-choice response selection. *Acta Psychologica*, *150*, 49–54.

Janczyk, M., Pfister, R., Hommel, B., & Kunde, W. (2014). Who is talking in backward crosstalk? Disentangling response- from goal-conflict in dual-task performance. *Cognition*, *132*, 30–43.

Janczyk, M., Pfister, R., Wallmeier, G., & Kunde, W. (2014). Exceptions to the PRP effect? A comparison of prepared and unconditioned reflexes. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *40*, 776–786.

Janczyk, M., Yamaguchi, M., Proctor, R. W., & Pfister, R. (2015). Response–effect compatibility with complex actions: The case of wheel rotations. *Attention, Perception, & Psychophysics*, *1–11*.

Karlin, L., & Kestenbaum, R. (1968). Effects of number of alternatives on the psychological refractory period. *The Quarterly Journal of Experimental Psychology*, *20*(2), 167–178.

Keller, P. E., & Koch, I. (2006). Exogenous and endogenous response priming with auditory stimuli. *Advances in Cognitive Psychology*, *2*(4), 269–276.

Kiesel, A., & Hoffmann, J. (2004). Variable action effects: Response control by context-specific effect anticipations. *Psychological Research*, *68*(2–3), 155–162.

Kunde, W. (2001). Response–effect compatibility in manual choice reaction tasks. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 398-394.

Kunde, W. (2003). Temporal response–effect compatibility. *Psychological Research*, *67*, 153–159.

Kunde, W., Koch, I., & Hoffmann, J. (2004). Anticipated action effects affect the selection, initiation, and execution of actions. *Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology*, *57*, 87–106.

Kunde, W., Landgraf, F., Paelecke, M., & Kiesel, A. (2007). Dorsal and ventral processing under dual-task conditions. *Psychological Science*, *18*, 100–104.

Kunde, W., Müsseler, J., & Heuer, H. (2007). Spatial compatibility effects with tool use. *Human Factors*, *49*, 661–670.

Kunde, W., Pfister, R., & Janczyk, M. (2012). The locus of tool-transformation costs. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(3), 703–714.

Lotze, H. (1852). *Medicinische Psychologie oder Physiologie der Seele*. Amsterdam: E. J. Bonset.

Massaro, D. W. (1990). An information-processing analysis of perception and action. In O. Neumann, & W. Prinz (Eds.), *Relationships between perception and action: Current approaches* (pp. 133–166). Berlin: Springer.

McCann, R. S., & Johnston, J. C. (1992). Locus of the single-channel bottleneck in dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance*, *18*(2), 471–484.

McClelland, J. L. (1979). On the time relations of mental processes: An examination of systems of processes in cascade. *Psychological Review*, *86*, 287–330.

Miller, J., & Reynolds, A. (2003). The locus of redundant-targets and non-targets effects: Evidence from the psychological refractory period paradigm. *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 1126–1142.

Paelecke, M., & Kunde, W. (2007). Action–effect codes in and before the central bottleneck: Evidence from the psychological refractory period paradigm. *Journal of Experimental Psychology: Human Perception and Performance*, *33*(3), 627–644.

Pashler, H. (1984). Processing stages in overlapping tasks: Evidence for a central bottleneck. *Journal of Experimental Psychology: Human Perception and Performance*, *10*, 358–377.

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin*, *116*, 220–244.

Pashler, H., & Johnston, J. C. (1989). Chronometric evidence for central postponement in temporally overlapping tasks. *Quarterly Journal of Experimental Psychology*, *41A*, 19–45.

Pfister, R., Dolk, T., Prinz, W., & Kunde, W. (2014). Joint response–effect compatibility. *Psychonomic Bulletin & Review*, *21*(3), 817–822.

Pfister, R., & Janczyk, M. (2013). Confidence intervals for two sample means: Calculation, interpretation, and a few simple rules. *Advances in Cognitive Psychology*, *9*, 74–80.

Pfister, R., Janczyk, M., Gressmann, M., Fournier, L. R., & Kunde, W. (2014). Good vibrations? Vibrotactile self-stimulation reveals anticipation of body-related action effects in motor control. *Experimental Brain Research*, *232*(3), 847–854.

Pfister, R., Janczyk, M., Wirth, R., Dignath, D., & Kunde, W. (2014). Thinking with portals: Revisiting kinematic cues to intention. *Cognition*, *133*, 464–473.

Pfister, R., Kiesel, A., & Melcher, T. (2010). Adaptive control of ideomotor effect anticipations. *Acta Psychologica*, *135*(3), 316–322.

Pfister, R., & Kunde, W. (2013). Dissecting the response in response–effect compatibility. *Experimental Brain Research*, *224*(4), 647–655.

Pfister, R., Melcher, T., Kiesel, A., Dechent, P., & Gruber, O. (2014). Neural correlates of ideomotor effect anticipations. *Neuroscience*, *259*, 164–171.

Pfister, R., Pfeuffer, C. U., & Kunde, W. (2014). Perceiving by proxy: Effect-based action control with unperceivable effects. *Cognition*, *132*(3), 251–261.

Prinz, W. (1987). Ideo-motor action. In H. Heuer, & A. F. Sanders (Eds.), *Perspectives on perception and action* (pp. 47–76). Hillsdale, NJ: Erlbaum.

Rieger, M. (2007). Letters as visual action–effects in skilled typing. *Acta Psychologica*, *126*, 138–153.

Ruthruff, E., Miller, J. O., & Lachmann, T. (1995). Does mental rotation require central mechanisms? *Journal of Experimental Psychology: Human Perception and Performance*, *21*, 552–570.

Sanders, A. F. (1980). Stage analysis of reaction processes. In G. E. Stelmach, & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 331–354). Amsterdam: North-Holland.

Sanders, A. F. (1998). Elements of human performance: Reaction processes and attention in human skill. In F. S. Andries (Ed.), Mahwah, N.J.: Erlbaum.

Schubert, T. (1999). Processing differences between simple and choice reactions affect bottleneck localization in overlapping tasks. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(2), 408–425.

Schweickert, R. (1978). A critical path generalization of the additive factors method: Analysis of a Stroop task. *Journal of Mathematical Psychology*, *18*, 105–139.

Shin, Y. K., & Proctor, R. W. (2012). Testing boundary conditions of the ideomotor hypothesis using a delayed response task. *Acta Psychologica*, *141*(3), 360–372.

Smith, E. E. (1968). Choice reaction time: An analysis of the major theoretical positions. *Psychological Bulletin*, *69*(2), 77–110.

Van Selst, M., & Jolicoeur, P. (1994). Can mental rotation occur before the dual-task bottleneck? *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 905–921.

Van Selst, M., & Jolicoeur, P. (1997). Decision and response in dual-task interference. *Cognitive Psychology*, *33*, 266–307.

Welford, A. T. (1952). The 'psychological refractory period' and the timing of high-speed performance—A review and a theory. *The British Journal of Psychology. General Section*, *43*(1), 2–19.

Wirth, R., Pfister, R., Foerster, A., Huestegge, L., & Kunde, W. (2015). Pushing the rules: Effects and aftereffects of deliberate rule violations. *Psychological Research*. http://dx.doi.org/10.1007/s00426-015-0690-9 (in press).

Wirth, R., Pfister, R., & Kunde, W. (2015). Asymmetric transfer effects between cognitive and affective task disturbances. *Cognition and Emotion*. http://dx.doi.org/10.1080/02699931.2015.1009002 (ahead-of-print).

Yamaguchi, M., & Proctor, R. W. (2011). The Simon task with multi-component responses: Two loci of response–effect compatibility. *Psychological Research*, *75*, 214–226.

Zwosta, K., Ruge, H., & Wolfensteller, U. (2013). No anticipation without intention: Response–effect compatibility in effect-based and stimulus-based actions. *Acta Psychologica*, *144*, 628–634.