

Long-Term and Short-Term Action-Effect Links and Their Impact on Effect Monitoring

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People aim to produce effects in the environment, and according to ideomotor theory, actions are selected and executed via anticipations of their effects. Further, to ensure that an action has been successful and an effect has been realized, we must be able to monitor the consequences of our actions. However, action-effect links might vary between situations, some might apply for a majority of situations, while others might only apply to special occasions. With a combination of behavioral and electrophysiological markers, we show that monitoring of self-produced action effects interferes with other tasks, and that the length of effect monitoring is determined by both, long-term action-effect links that hold for most situations, and short-term action-effect links that emerge from a current setting. Effect monitoring is fast and frugal when these action-effect links allow for valid anticipation of action effects, but otherwise effect monitoring takes longer and delays a subsequent task. Specific influences of long-term and short-term links on the P1/N1 and P3a further allow to dissect the temporal dynamics of when these links interact for the purpose of effect monitoring.

Public Significance Statement

We show that self-produced action effects are monitored, and monitoring requires processing capacity. The difficulty of effect monitoring is determined by both long-term action-effect links that participants developed throughout their lifetime, and short-term action-effect links that emerge from the current setting.

Keywords: ideomotor theory, action effects, effect monitoring, P1/N1, P3a

Long-Term and Short-Term Action-Effect Links

There is one thing that we all have in common: In the morning, we stand in front of the mirror and brush our teeth. Grabbing the toothbrush is usually very easy, we just move our hand toward the tooth brush holder and grab the toothbrush. Simple. However, this

easy task might turn into a rather complicated endeavor with the following twist: Try not to focus on your actual hand, but to control the hand of the person in the mirror. When only indirect vision of hand and brush holder through a mirror is available, controlling movements toward and away from the mirror (or, in general, any movement in the direction orthogonal to the mirror plane) becomes painfully complicated, and most people will likely have trouble to even approach the toothbrush, will hesitate, or will instead even move their hand further away from it. However, with some practice, a new movement-outcome relationship is learned for that situation, so that the motion of the mirror image can be correctly anticipated, and the mirrored hand will become increasingly controllable (Rosenbaum, 1991).

This situation illustrates two types of movement-outcome links we might have. Long-term links that hold for the majority of situations we encounter in everyday life, and short-term links that might be equally reliable, but exist only for certain situations or time intervals. For example, long-term experience tells us that we usually produce spatially compatible outcomes with our actions.

This article was published Online First April 23, 2018.

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This work was supported by the German Research Foundation (Grants KU 1964/11-1, STE 1708/4-1, & JA 2307/3-1) within the DFG Priority Program 1772.

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Moving the computer mouse to the right usually produces cursor movements to the right side as well. However, this long-term link might be inverted at times such as when moving a lever with one pivot where movements to the right produce lever movements to the left (Janczyk, Pfister, & Kunde, 2012; Kunde, Müseler, & Heuer, 2007; Müseler, Kunde, Gausepohl, & Heuer, 2008). Of course, humans adapt to such situational demands, but they practically never reach the level of performance that is possible with natural long-term links (Kunde, Koch, & Hoffmann, 2004).

Ideomotor Theory

Movement-outcome links (the relationship between a response and its effect, R-E) are at the core of ideomotor theory, an action-control framework which holds that actions are selected and controlled by anticipating the effects that they will (later) produce (Elsner & Hommel, 2001; Harleß, 1861; Hommel, Müseler, Aschersleben, & Prinz, 2001; James, 1890). Thus, the theory assumes that motor actions are mentally stored and retrieved in terms of the sensory changes that these movements produce (Kunde, Schmidts, Wirth, & Herbort, 2017). Selecting a response means to anticipate its sensory effects. In line with this assumption, it is—for example—easier to produce a left stimulus with a left response key press (R-E compatible) than with a right response key press (R-E incompatible), with longer response times and sometimes also more errors (Janczyk, Durst, & Ulrich, 2017; Kunde, 2001; Pfister, Janczyk, Wirth, Dignath, & Kunde, 2014; Pfister & Kunde, 2013). In the end, a compatible R-E relation is the movement-outcome link that we are accustomed to. A strong formulation of the ideomotor theory assumes that motor actions are exhaustively represented by their sensory effects. Consequently, humans have no direct influence on their muscle activities, but can only access codes of the perceptual changes produced by these activities, which then trigger corresponding muscle activities. Actors might become aware of such effect anticipation, but even unconscious activation of effect codes seems to prime their associated motor patterns (Kunde, 2004).

In any case, response selection can only work if the effect is mentally linked to the motor pattern that is going to produce this effect. That is why the hand in the mirror can only be controlled adequately once a systematic, short-term relationship between movement and outcome has been established for that setting.

Effect Monitoring

If we assume that action selection revolves around the effects that these actions will (later) produce, then it becomes plainly obvious that there must be some mechanism that checks whether the intended effects have ultimately been realized. Only after a produced effect has been recognized and compared to the intended effect can we determine the success of an action. Hence, an effect monitoring process has been proposed that was assumed to draw on limited resources (Welford, 1952; see also Kunde, Wirth, & Janczyk, 2017).

There is in fact some evidence that effect monitoring in one task affects performance in another subsequent task: Specifically, monitoring of (spatially) incompatible effects takes

longer and thereby delays responses in a subsequent task more than monitoring compatible effects (Wirth, Janczyk, & Kunde, 2017), even when these effects are not task-relevant. For example, participants were asked to add a puzzle piece to a centrally presented one at the left or the right side by pressing a left or a right button (ideomotor task, see Wirth et al., 2017). Shortly after Task 1 was completed, a color patch or a letter had to be categorized in a simple classification task. Even though these tasks were unrelated and did not overlap in time, responses in Task 2 were slower if an incompatible effect had been produced in Task 1 rather than a compatible effect, which could plausibly only originate from the still ongoing processing of these effects. Even though the effects carry no necessary information for the participants, they are not simply ignored, but processed, which interferes with the processing of a separate task. Further, this observation thus shows that not only sensory feedback from continuous responses is monitored (for online control of actions, e.g., Bratzke, Rolke, & Ulrich, 2009; Jentzsch, Leuthold, & Ulrich, 2007; Ulrich et al., 2006; Wirth, Pfister, Brandes, & Kunde, 2016; Wirth, Pfister, Janczyk, & Kunde, 2015), but that even discrete effects produced by discrete responses are subject to such monitoring as well.

One possibility to explain the prolongation of action effect monitoring for incompatible action effects is to assume that previously acquired R-E links induce an expectation about an upcoming effect. Effect monitoring is facilitated if this expectation is confirmed, but prolonged if this expectation is violated. In this context, expectation is not necessarily associated with a subjective feeling of expectation, but simply refers to the anticipation of an external event in the cognitive system. Indeed, there is evidence that it is harder, and conceivably takes longer, to process action effects that violate expectations based on previous experience than action effects that do not (Desantis, Roussel, & Waszak, 2014). Here, participants were asked to identify the effects of button presses, namely dot movements that were directed upward or downward. Crucially, these effects could be congruent or incongruent to the R-E relation (e.g., left key produces downward movement, right key produces upward movement) that was acquired during a preceding learning phase. Participants identified more accurately effects that they expected based on their learning experience.

Assuming that actions typically produce spatially compatible sensory effects (e.g., moving the right hand usually produces visual feedback on the right side of the body) we assume that expectations based on long-term experience favor the processing of spatially compatible sensory effects. However, such long-term experience may be changed or perhaps even be replaced by more recent experience, such that in a current experimental context, an action with the right hand produces visual events on the left side. This might establish short-term links that oppose participants' long-term experience. In general, this means that the impact of long-term links would favor monitoring of spatially compatible effects irrespective of the current setting, whereas the impact of short-term links would favor monitoring of the currently frequent R-E pairs. The joint impact of such long-term and short-term experience on effect monitoring is addressed in the present study.

Function and Consequences of Long-Term and Short-Term Action-Effect Links

The function of monitoring self-produced effects has been described as both *screening for* and *validation of* links between responses and effects in the environment (Wirth et al., 2017). While the *screening* function checks for any new occurrences in the environment that correlate with an action (providing a means to build up R-E links for using them for later action selection), the *validation* function re-evaluates whether already established R-E relations are still valid. In that sense, the *validation* function employs long-term R-E links that apply to a multitude of situations (moving the hand forward usually moves the hand further away), while the *screening* function is additionally attuned to new situations to structure external occurrences and identify possible short-term covariations (moving the hand forward moves the mirror hand closer).

The consequences of these *screening* and *validation* functions are manifold. As already indicated above, effect monitoring could be at the base of identifying prediction errors, thereby triggering the recalibration of established long-term R-E links if they are no longer valid (Gaveau, Prablanc, Laurent, Rossetti, & Priot, 2014; Shadmehr, Smith, & Krakauer, 2010; Tseng, Diedrichsen, Krakauer, Shadmehr, & Bastian, 2007). Moreover, predicted effects should come with a higher feeling of agency, the subjective feeling of having caused that effect (Gentsch & Schütz-Bosbach, 2011), and participants should even experience temporal attraction between the response and the effect (Haggard, Clark, & Kalogeras, 2002; see Moore & Obhi, 2012, for a review on agency and temporal binding).

The Interplay of Long-Term and Short-Term Action-Effect Links

Both long-term and short-term links shape performance: In an experimental environment without a consistent R-E relationship, pre-experimentally acquired long-term links seem to be at work, because even when actions produce compatible and incompatible effects in a random manner, it still takes slightly longer to monitor incompatible as compared to compatible effects (an observation we replicate in Exp. 1, cf. Wirth et al., 2017). Yet, when strong short-term links can emerge by introducing a deterministic R-E relationship in the experiment (only compatible or incompatible effects), they additionally influence performance: Monitoring speeds up when short-term links imply the production of compatible effects, just as long-term links do, whereas monitoring slows down when short-term links imply the production of incompatible effects and thus contradict long-term links.

These setups, however, are somewhat artificial, because they employ totally random or totally deterministic R-E links. But usually, the outcome of an action is neither fully determined nor completely random. If we push down the door handle, the door usually opens, but it might be locked at times. If we hit the light switch, the room usually lights up, but the bulb might be broken. With the current experiments, we set out to explore the interplay of long-term and short-term action-effect links and their influence on effect monitoring in situations that are neither fully deterministic nor completely random. In the present experiments, responses produced one spatial effect in most of the cases (i.e., the expected

effect, according to short-term links), and the opposite effect in a fraction of the trials (i.e., the unexpected effect). Briefly after this ideomotor task (Task 1) was completed, the stimulus of a simple classification task (Task 2) was presented to measure any aftereffects of producing and monitoring compatible versus incompatible and expected versus unexpected effects onto subsequent performance (Experiment 1). Finally, as a further measure, we recorded EEG in a slightly adjusted design to identify ERP markers of effect monitoring after response production in the ideomotor task (Experiment 2).

Experiment 1

In Experiment 1, we tested whether the duration of effect monitoring is determined by long-term action-effect links, and whether it can be modulated by manipulations rendering (additional) short-term links likely: Monitoring might speed up when short-term links imply the production of compatible effects, just as long-term links do, whereas monitoring might slow down when short-term links imply the production of incompatible effects and thus contradict long-term links. To this end, we presented participants with a puzzle piece at the center of the screen and asked them to add another puzzle piece at the top or at the bottom by pressing an upper or a lower key. Crucially, the chance of producing a puzzle piece at the desired location was probabilistic, and this probability was manipulated between blocks: In high-compatible blocks, keypresses would produce a spatially compatible effect (i.e., a puzzle piece appearing at the location of the key press) in 75% of the trials, and a spatially incompatible effect in only 25% of the trials. In high-incompatible blocks, these probabilities were reversed. Via this frequency manipulation, both long-term links and short-term links could manifest: Long-term links that might trigger the expectation of compatible effects irrespective of the current setting, and short term links that might trigger effect expectations¹ based on the more frequent relationship in the current setting. Finally, in a random block, keypresses and effect locations were uncorrelated, so that no short-term action-effect link could be derived in this setting (as a measure of pure long-term associations without a short-term influence). After a response-stimulus onset interval (RSOI) of 50 ms after a puzzle piece was added to the top or the bottom via pressing the upper or lower response key (Task 1), a simple classification task followed (Task 2) and required participants to categorize a letter that was displayed at the center of the screen. This dual-task setup was chosen because the monitoring process of interest here likely takes place *after* a response in Task 1 has been completed. Therefore, we analyzed Task 2 performance to measure the aftereffects of monitoring (in)compatible and (un)expected action effects.

Three possible outcomes are conceivable: First, it could be that monitoring incompatible effects delays Task 2 responses relative to monitoring compatible effects even when incompatible effects appear (more) frequently. This would suggest that long-term links are dominant and unaffected by short-term links. Second, it could

¹ Again, keep in mind that “expectation” based on long-term and short-term links here does not imply a concrete subjective feeling of expectation, nor does it refer to external events in the near or far future (cf. Jordan, 2013), but simply refers to the anticipation of an external event in the cognitive system.

be that monitoring of overall unexpected effects (incompatible effects when compatible effects are frequent; compatible effects when incompatible effects are frequent) leads to delays in Task 2. This would suggest that long-term links can easily be replaced by short-term links. Finally, response delays after incompatible effects might emerge only when incompatible effects are rare, and possibly vanish with an increasing frequency of incompatible effects. This would mean that both short-term and long-term links exert a joint influence, with long-term and short term links prompting convergent predictions when compatible effects are frequent, and divergent predictions if they are infrequent. Alternatively, this pattern of results could suggest that only in case of converging long-term and short-term links, long-term links are employed, whereas with opposing links, no predictions are derived at all.

Method

Participants. Forty-eight participants were recruited (15 male; 2 left-handed; mean age = 28.2 years, $SD = 9.0$) 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. Two participants were removed from the sample due to improper task execution (long sequences of identical keypresses, even though participants were instructed to choose their option spontaneously while maintaining an approximately equal ratio between top and bottom keypresses).

Apparatus and stimuli. S1 were pictures of puzzle pieces with a connector at the top and the bottom, presented centrally on the screen (5° visual angle). Participants had to add a puzzle piece at the top or at the bottom and they were encouraged to choose their option spontaneously while maintaining an approximately equal ratio between top and bottom keypresses. Responses were given with the left hand on the upper “E” and lower “X” keys of a standard QWERTZ keyboard. These keypresses instantly produced puzzle pieces at either the top or the bottom of the screen as Effect 1 (E1). For Task 2, participants had to discriminate a letter (H vs. S, 2° visual angle) that was presented centrally in the S1 puzzle piece and required a right-hand response on the “N” or “M” keys (see also Figure 1). Additionally, the stimulus letters were presented with varying contrast (high contrast: white letter against black background; low contrast: gray letter against black background). This perceptual manipulation served to replicate previous results, determining the information processing stage in Task 2 that interferes with effect monitoring of Task 1 (for more details, see

Wirth et al., 2017, Exp. 2 & 3). S2 quality was varied within participants; letter-response mapping was counterbalanced between subjects. All stimuli were presented on a 22-inch screen with a refresh rate of 60Hz against a black background using EPrime 2.

The R-E mapping (spatially compatible: lower key produces bottom puzzle piece, upper key produces top puzzle piece, vs. incompatible: lower key produces top puzzle piece, upper key produces lower puzzle piece) in Task 1 was manipulated within participants, with blocks that produced mainly spatially compatible effects (high-compatible blocks: 75% compatible effects, 25% incompatible effects) and blocks that produced mainly incompatible effects (high-incompatible blocks: 25% compatible effects, 75% incompatible effects). However, the identity of an effect could not be predicted on a given trial; high-compatible blocks only had a higher probability of presenting a compatible over an incompatible effect and vice versa, and the block conditions were not explicitly instructed. Finally, in a third condition, no expectations of the upcoming effect could be raised (random blocks: 50% compatible, 50% incompatible). This random condition, served to replicate previous findings on long-term links (Wirth et al., 2017, Exp. 5a & 5b). The order of the first two block conditions (first high-compatible blocks vs. first high-incompatible blocks) was counterbalanced between participants, and the random blocks were always presented last. Participants completed 15 blocks, 5 blocks per block condition (high-compatible and high-incompatible blocks in counterbalanced order, random blocks always last). So half of the participants were presented with 5 high-compatible, then 5 high-incompatible, and 5 random blocks, while the other half started with 5 high-incompatible blocks, followed by 5 high-compatible and 5 random blocks. Each block contained 64 trials made up of 48 dual task trials (75%) and 16 single task trials (25%). The intermixed single task trials with only Task 1 were included to prepare for the EEG-study (Experiment 2). After a puzzle piece was produced in these trials, participants simply waited for the next trial to start. In the EEG-study, these trials would allow us to analyze the electrophysiological signature of effect monitoring isolated from any processes that Task 2 might add. The proportion of dual and single task trials was chosen so that, overall, participants expected upcoming trials to include Task 2 and to prepare accordingly. This would later allow us to estimate the physiological correlates that we expect in dual task trials in a single task setting.

Procedure. The trial procedure is illustrated in Figure 1. A fixation cross marked the beginning of a trial. After 500 ms, S1 was presented centrally on the screen and required the production of E1 via pressing the upper or lower key. E1 occurred immediately after R1. In a high-compatible block, keypresses produced a spatially compatible effect with a 75% probability and a spatially incompatible effect with a 25% probability. In high-incompatible blocks these probabilities were reversed, and in random blocks, compatible and incompatible effects were equally likely. The effects remained on screen until the end of the trial, so that the offset of the effects would not draw further attention. If after a maximum of 2000 ms, no key was pressed, the trial counted as an omission and no E1 was displayed.

In case of a single task trial, nothing further happened and participants simply waited for 800 ms until the next trial would start. In a dual task trial, after an RSOA of 50 ms after R1, S2 was

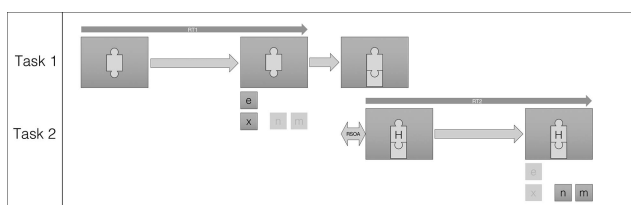


Figure 1. Trial procedure of the experiments. In Task 1, a puzzle piece had to be added at the top or the bottom of a centrally presented piece by pressing an upper or lower button. This response started the response-stimulus onset asynchrony (RSOA), after which a second stimulus within the puzzle piece (letters H or S) appeared and had to be classified.

displayed within S1 and called for the second response. The two tasks were always presented in that order, and there was no temporal overlap between the task events (i.e., stimuli, effects, or responses of Task 1 and stimuli or responses in Task 2).

Participants could not commit any errors in Task 1, but if the wrong response was given in Task 2, written feedback was presented after R2 (“Letter task: Error!”) for 500 ms in red color. Equally in case of omissions, feedback was presented at the end of the trial (“Puzzle task: Too slow!” or “Letter task: Too slow!”). If both tasks were completed correctly, the next trial started immediately, indicated by the fixation cross.

Data Treatment

For reaction time (RT) analyses, we excluded trials with omissions (Task 1: 1.0%, Task 2: 0.1%) and errors (Task 2: 3.5%). The remaining trials were screened for outliers and we removed trials in which RTs for any task deviated more than 2.5 standard deviations from the corresponding cell mean, computed separately for each participant and experimental condition (8.7%). Overall, 13.3% of the trials were removed. The remaining data were then analyzed separately depending on their block condition: As the order of high-compatible and high-incompatible blocks were counterbalanced between subjects, RTs of these blocks were analyzed in a $2 \times 2 \times 2$ ANOVA with current R-E compatibility (compatible effect vs. incompatible effect), block condition (high-compatible block vs. high-incompatible block) and S2 quality (high contrast vs. low contrast) as within-subjects factors. Random blocks were always presented last, and consequently, all participants had experienced both, the high-compatible and the high-incompatible blocks, in advance. Therefore, random blocks were analyzed separately in a 2×2 ANOVA with current R-E compatibility (compatible effect vs. incompatible effect), and S2 quality (high contrast vs. low contrast) as within-subjects factors. Error rates in Task 2 were analyzed accordingly.

Results

Overall, upper and lower responses in Task 1 were chosen with an approximately equal ratio (upper key: 50.5%, lower key 49.5%, $t(45) = 0.22$, $p = .824$, $d = 0.03$).

High-compatible and high-incompatible blocks. None of the experimental factors influenced RT1. This was true for single task trials, $F_s < 1$, $p_s > .325$, as well as for dual task trials, $F_s < 1.91$, $p_s > .174$.

In Task 2, responses were faster after compatible effects in Task 1 (476 ms), than after incompatible effects (481 ms), but this effect missed conventional levels of statistical significance, $F(1, 45) = 4.05$, $p = .050$, $\eta_p^2 = .08$. Current compatibility interacted with block condition, $F(1, 45) = 13.30$, $p = .001$, $\eta_p^2 = .23$ (see Figure 2A)², with an effect of current compatibility only in high-compatible blocks ($\Delta = 13$ ms, $t(45) = 3.71$, $p = .001$, $d = 0.55$) and no effect in high-incompatible blocks ($\Delta = -3$ ms, $t(45) = -1.10$, $p = .278$, $d = -0.16$). This difference, however, is neither clearly driven by responses after compatible trials speeding up in high-compatible blocks (relative to responses after compatible trials in high-incompatible blocks, $\Delta = 8$ ms, $t(45) = 1.33$, $p = .191$, $d = 0.20$), nor by a clear response slowdown after incompatible effects in high-compatible blocks (relative to responses after incompatible effects in

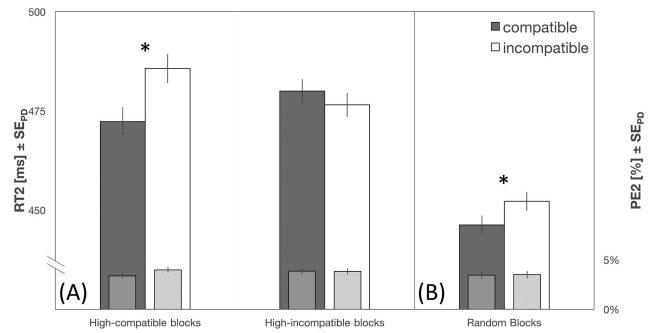


Figure 2. Results of Experiment 1. Response times (RT2) and percentage of errors (PE2) for Task 2, separately for blocks where short-term links could be expressed (A) and random blocks (B). Gray bars represent trials that presented a spatially compatible effect in Task 1, white bars represent trials with an incompatible effect. Error bars denote the standard error of paired differences, computed separately for each comparison of compatibility (Pfister & Janczyk, 2013). * $p < .050$.

high-incompatible blocks, $\Delta = -9$ ms, $t(45) = 1.59$, $p = .118$, $d = 0.23$), but most likely by a combination of both influences. Further, there was a main effect of S2 quality, $F(1, 45) = 20.52$, $p < .001$, $\eta_p^2 = .31$, with faster responses to targets with a high contrast (470 ms) compared to targets with a low contrast (487 ms). However, there was no significant interaction including the factor S2 quality, and overall no other effects reached significance, $F_s < 1.58$, $p_s > .215$.

In the error rates of Task 2, neither the main effects nor any interaction was significant, $F_s < 1.85$, $p_s > .180$.

Random blocks. Again, none of the experimental factors influenced the performance in Task 1. This was true for single task trials, $F < 1$, $p = .276$, as well as for dual task trials, $F_s < 1$, $p_s > .503$.

In Task 2, there was a significant effect of current compatibility, $F(1, 45) = 5.28$, $p = .026$, $\eta_p^2 = .11$ (see Figure 2B), with faster responses after a compatible (446 ms) than after an incompatible effect (481 ms). Further, there was an effect of S2 quality, $F(1, 45) = 13.37$, $p = .001$, $\eta_p^2 = .23$, with faster responses to targets with a high contrast (443 ms) compared to targets with a low contrast (456 ms). However, there was no interaction between the two factors, $F < 1$, $p = .601$.

In the error rates of Task 2, neither main effects nor interaction were significant, $F_s < 2.05$, $p_s > .159$.

Discussion

In Experiment 1, we tested whether and how long-term and short-term action-effect links influence the length of the effect monitoring process. First, let's consider the random blocks. Here, the setting did not allow for any short-term links to be shaped, so

² Based on the suggestion of two anonymous reviewers, we had a further look into the time-course of these effects as a post hoc analysis. We therefore reaggreated the data separately for each block (1–5) within each frequency condition (high-compatible vs. high-incompatible) and re-ran the ANOVA including this factor. While participants became faster from the first block to the last block within each frequency condition, $F(4, 39) = 10.07$, $p < .001$, $\eta_p^2 = .51$, there is no interaction including the factor block, $F_s < 1$. This suggests that the compatibility effect does not change significantly during each frequency condition.

effect monitoring is purely influenced by the long-term links that participants have acquired. The results of the Task 2 analysis replicate previous results and seem to indicate that participants automatically expect to produce spatially compatible effects (cf. Wirth et al., 2017, Exp. 5a & 5b). After all, a compatible spatial R-E relation is what people are used to, if they snap their right hand, they produce a sound on their right side. Monitoring of compatible effects is completed faster relative to incompatible effects, and consequently a subsequent task can be performed and completed earlier.

Further, the data suggest that both, the long-term links that participants acquired in years of interacting with the environment, and short-term links elicited by the current setting, shape the duration of the effect monitoring process. Usually, participants expect to produce effects that are spatially compatible with their response (cf. random blocks). And in high-compatible blocks, the short-term setting reinforces the long-term links, so they can play in concert and render the monitoring of expected, spatially compatible action effects quick and easy. On the other hand, unexpected incompatible effects in this setting pose a greater difficulty for the effect monitoring process, and a subsequent task is delayed even further. In the high-incompatible blocks, long-term and short-term links suggest opposite predictions: While participants usually produce spatially compatible effects, the current setting now confronts them with mainly incompatible action effects. In this case, either both types of expectations cancel each other out, or the contradiction between both links results in no predictions about the upcoming effect at all.

Finally, the additive combination of Task 1 compatibility and S2 quality replicates previous results from a line of research that aimed at localizing the information processing stage of Task 2 which interferes with effect monitoring. Briefly, this result again suggests that effect monitoring delays a subsequent task as a whole, not just those processes that are assumed to be capacity limited (see Wirth et al., 2017, Experiments 2 & 3 for more details).

Experiment 2

Experiment 2 aimed (a) to replicate important behavioral results obtained in Experiment 1, and (b) to identify electrophysiological markers that reflect this pattern of results. Hence, a slightly modified version of Experiment 1 was designed and optimized for EEG analysis. Monitoring of action effects might be mirrored on the neural level by various forms of cortical activity reflecting the processing of external events. Because the present study focused on the influence of short-term and long-term R-E links on the expectedness of action effects, we considered well-known markers of the time course of visual attention and stimulus evaluation that have previously been found to reflect manipulations of stimulus expectedness.

An important early ERP component linked to attentional processing of stimuli is the visual N1 (Luck & Kappenman, 2012; Mangun, 1995), an occipital negativity that peaks around 200 ms after stimulus onset. Studies have shown that the N1, similar to the preceding P1, is increased for stimuli that are presented at an attended (e.g., Eason, Harter, & White, 1969; Di Russo, Martínez, & Hillyard, 2003) or expected position (e.g., Luck et al., 1994; Mangun & Hillyard, 1991). As the N1 is also sensitive to several

physical characteristics of the stimulus, it is argued that this ERP effect reflects an early capacity-limited process of feature discrimination that facilitates processing at the expected and attended location, whereas the P1 is more likely linked to suppressing the unexpected, unattended location (Luck & Hillyard, 1995; Luck et al., 1994; Mangun & Hillyard, 1991).

Studies that investigate the processing of rare, unexpected target stimuli within a continuous sequence of distractor stimuli commonly find a strong positivity peaking between 250 and 500 ms after the onset of the infrequent target, the P3 (Bashore & van der Molen, 1991; Polich, 2007; Sutton, Braren, Zubin, & John, 1965), although its latency was shown to vary with the difficulty to detect and classify the target stimulus (Kutas, McCarthy, & Donchin, 1977; Magliero, Bashore, Coles, & Donchin, 1984). Comparing infrequent target stimuli with equally infrequent, but task irrelevant distractors showed that the P3 in fact consists of two separate components: an earlier, fronto-central P3a is elicited by infrequent distractors, whereas a later, parietal P3b is associated only with task- and response-relevant target stimuli (Conroy & Polich, 2007; Snyder & Hillyard, 1976; Squires, Squires, & Hillyard, 1975; Verleger, Jaskowski, & Wascher, 2005). It was suggested that the P3a represents an early attention process that signals changes in working memory representation and involves activity in dopaminergic pathways (Polich, 2007; Polich & Criado, 2006) while the P3b mirrors the transition of this attention-driven signal to temporal and parietal structures, leading to increased release of norepinephrine, which in turn improves the signal-to-noise ratio and therefore facilitates stimulus processing (Dayan & Yu, 2006; Nieuwenhuis, Aston-Jones, & Cohen, 2005; Sara & Bouret, 2012; Servan-Schreiber, Printz, & Cohen, 1990).

Although these ERP components have predominantly been examined by means of other paradigms such as the Posner cuing task (N1) and the oddball task (P3), the action effects elicited by responses in our paradigm share key features of the stimuli that elicit these components: spatially compatible effects appear at the expected position, whereas incompatible effects are unexpected and presented at an odd position. For this reason, both the visual N1 and the P3a appear to be promising possible markers of effect monitoring. As the action effect in our paradigm is of no relevance to the actual task and would in no way be utilized to initiate upcoming responses (Verleger et al., 2005), though, the task-related P3b is unlikely to be prominent at all. Overall, we assume spatially incompatible action effects to be processed as unexpected “oddball” events (according to long-term links) and thus being accompanied by increased amplitudes in these ERPs. The possibly different influence of long-term links and short-term links on N1 and P3a may be examined when studying the relationship of current compatible and incompatible trials in high-incompatible blocks. If short-term links dominate action effect processing, compatible action effects should elicit a larger N1 or P3a than current incompatible trials in high-compatible blocks and vice versa in high-incompatible blocks, as these are the more likely and therefore more expected events. If long-term links are dominant, though, compatible action effects should elicit a larger N1 or P3a irrespective of block condition. Therefore, also in high-compatible blocks, increased ERP amplitudes should be associated with incompatible action effects. Nonetheless, one finding of Experiment 1 was that monitoring of compatible effects is completed faster, especially in high-compatible blocks. Hence, we expect ERP amplitude differences between com-

patible and incompatible trials to be smaller in high-incompatible blocks. If this reduction is apparent already in the N1 time range or later during the P3a time range depends on whether this counteracting of long-term and short-term links occurs early or late during the time course of attentional processes.

Method

Thirty-two new participants were recruited (7 male; 3 left-handed; mean age = 22.2 years, $SD = 2.8$) and received monetary compensation. They fulfilled the same criteria as in Experiment 1. Two participants were removed from the sample due to improper execution of Task 1 (more than 1000 consecutive identical keypresses, even though participants were instructed to choose their option spontaneously while maintaining an approximately equal ratio between top and bottom keypresses).

To test the electrophysiological signature of effect monitoring, Experiment 1 was modified and reduced to the most important components: Both the random blocks and the S2 quality manipulation were omitted to improve the power for the critical interaction that was observed in Experiment 1 (see Figure 2A). Further, the duration of the fixation cross was jittered (from 450 to 550 in 16.6 ms steps) and the RSOA between E1 and S2 was now manipulated (50 ms vs. 150 ms). This was done to address the temporal dynamics of effect monitoring and to see whether an influence of the R-E compatibility of Task 1 can be found even with longer temporal separation of the tasks. Finally, the proportion of single task trials was increased (from 25% to 33%) to improve the signal to noise ratio in single task trials that would provide the cleanest correlate of effect monitoring, because no subsequent cognitive or motor processes are required here. To account for this change, participants now completed 30 blocks, 15 blocks per block condition (high-compatible and high-incompatible blocks in counterbalanced order), of 72 trials each, with 48 dual task trials and 24 single task trials.

EEG was recorded from 64 electrodes via a BIOSEMI Active-Two system (BioSemi, Amsterdam, The Netherlands; channels Fp1, AF7, AF3, F1, F3, F5, F7, FT7, FC5, FC3, FC1, C1, C3, C5, T7, TP7, CP5, CP3, CP1, P1, P3, P5, P7, P9, PO7, PO3, O1, Iz, Oz, POz, Pz, CPz, Fpz, Fp2, AF8, AF4, AFz, Fz, F2, F4, F6, F8, FT8, FC6, FC4, FC2, FCz, Cz, C2, C4, C6, T8, TP8, CP6, CP4, CP2, P2, P4, P6, P8, P10, PO8, PO4, O2 as well as the left and right mastoid, relative to common mode sense (CMS) and driven right leg (DRL) electrodes). Vertical and horizontal electrooculogram (EOG) was recorded from electrodes above and below the right eye and on the outer canthi of both eyes. EEG and EOG data were continuously recorded at a sampling rate of 512 Hz. All electrodes were off-line rereferenced to linked mastoids and band-pass filtered to 0.1 – 40 Hz.

Data Treatment

For the analysis of the behavioral data, we again removed trials with omissions (Task 1: 0.7%, Task 2: 0.2%) and errors (Task 2: 3.3%). The remaining trials were screened for outliers and we removed trials in which RTs for any task deviated more than 2.5 standard deviations from the corresponding cell mean, computed separately for each participant and experimental condition (7.6%). Overall, 11.8% of the trials were removed. RTs were now analyzed

via a $2 \times 2 \times 2$ ANOVA with current R-E compatibility (compatible effect vs. incompatible effect), block condition (high-compatible block vs. high-incompatible block) and RSOA (short: 50 ms vs. long: 150 ms) as within-subjects factors. Error rates in Task 2 were analyzed accordingly.

The analysis of the EEG data was conducted using custom-made MATLAB v8.3 (The Mathworks, Natic, MA, U.S.A.) scripts together with EEGLAB v13.5 (Delorme & Makeig, 2004) functions. First, EEG data were epoched to 800 ms before and 1500 ms after the response of Task 1, which coincides with the presentation of the action effect. The baseline of these epochs was corrected to the interval of 150–50 ms before Task 1 response (e.g., Ridderinkhof, Nieuwenhuis, & Bashore, 2003; Dudschig & Jentzsch, 2009). Subsequently, electrodes with poor data quality were interpolated with data material from surrounding electrodes using spherical spline interpolation if they met the joint probability criterion (threshold 5) as well as the kurtosis criterion (threshold 10) in EEGLAB's channel rejection routine (pop_rejchan.m; mean electrodes interpolated per participant = 3.5). Following this, epochs were excluded on the basis of three criteria: (a) epochs with activity deviating more than 300 μ V from the baseline in any electrodes except Fp1, Fpz, Fp2, Af7, and Af8 (a conservative threshold and the exclusion of the most frontal electrodes were applied because blinks and eye movements were corrected in a later stage; see, e.g., Carlson, Foti, Mujica-Parodi, & Hajcak, 2011; Steinhauser, Maier, & Steinhauser, 2017); (b) epochs whose joint probability deviated more than 5 standard deviations from the epoch mean; (c) epochs that had RTs in Task 1 longer than 1500ms. Overall, 6.0% of epochs were removed. To correct for muscular artifacts and eyeblinks, an infomax-based independent component analysis (Bell & Sejnowski, 1995) was conducted. Independent components with time courses and topographies typical for such artifacts were removed after visual inspection and epochs were averaged separately for each participant and condition. As the ERPs in question have previously been investigated with different paradigms, the exact latencies of possible effects could not be established a priori (particularly for the P3, which was observed to differ in latency with regard to task difficulty, see Magliero et al., 1984). For this reason, we first defined broad time windows of 150–250 ms at electrode POz for the N1 (Luck & Kappenman, 2012) and 250–500 ms at electrode FCz for the P3a (Polich, 2007). Utilizing the Mass Univariate ERP Toolbox (Groppe, Urbach, & Kutas, 2011), we then conducted cluster-based permutation tests (Bullmore et al., 1999) on ERP difference waves of the respective conditions at these time windows to control for the familywise error (FWE) rate, with 100,000 permutations and a cluster inclusion threshold of $p = .050$. To increase test power and because all our effects are expected to last more than 10 ms, we followed the recommendation of Groppe et al. (2011) and downsampled the data by a factor of 5.12 to 100 Hz before testing.

Results

Behavioral data. Overall, upper and lower responses in Task 1 were chosen with a slight, descriptive preference for the lower key (upper key: 46.8%, lower key 53.2%, $t(29) = 1.75$, $p = .090$, $d = 0.32$).

Again, none of the experimental factors influenced RT1. This was true for single task trials, $F_s < 2.07$, $p_s > .161$, as well as for dual task trials, $F_s < 2.12$, $p_s > .156$.

In Task 2, there was a significant main effect of current compatibility, $F(1, 29) = 6.24$, $p = .018$, $\eta_p^2 = .18$, with faster responses after a compatible (466 ms) than after an incompatible effect (472 ms). The interaction between block condition and current compatibility that emerged in Experiment 1 did not turn significant here, $F(1, 29) = 2.22$, $p = .147$, $\eta_p^2 = .07$ (see Figure 3), but exploratory post hoc analyses revealed a significant compatibility effect in high-compatible blocks ($\Delta = 10$ ms, $t(29) = 2.11$, $p = .043$, $d = 0.39$) but not in high-incompatible blocks ($\Delta = 3$ ms, $t(29) = 1.77$, $p = .086$, $d = 0.32$).³ Further, there was a main effect of RSOA, $F(1, 29) = 26.42$, $p < .001$, $\eta_p^2 = .48$, with faster responses after a long RSOA (463 ms) compared to responses after a short RSOA (475 ms). No other effects reached significance, $F_s < 1.68$, $p_s > .205$.

In Task 2 error rates, there was a significant main effect of RSOA, $F(1, 29) = 15.18$, $p = .001$, $\eta_p^2 = .34$, with more errors after a long interval (5.7%) than after a short interval (4.2%). No other effects reached significance, $F_s < 1.24$, $p_s > .274$.

EEG data. As ERP correlates of effect monitoring in dual task trials may strongly overlap with neural activity evoked by Task 2 processing, we analyzed ERP activity locked to the Task 1 response (and hence, the onset of the action effect) in single-task trials only (see Figures 4 and 5). To this end, we subjected difference waves for the within-subjects factors current R-E compatibility (compatible effect minus incompatible effect) and block condition (high-compatible block minus high-incompatible block) as well as for the interaction term [(compatible minus incompatible in high-compatible blocks) minus (compatible minus incompatible in high-incompatible blocks)] to cluster-based permutation tests. As the response to the puzzle task and the onset of the action effect

occur at the same time, it is possible that action-effect related and response-related brain activity overlap in time. However, the overall observed ERP components strongly match the succession of ERP components typically found following visual stimuli.

For the visual N1 (see Figure 4), current compatible trials exhibit a more pronounced negativity than incompatible trials, as revealed by a significant cluster between 160 and 200 ms relative to action-effect onset ($p = .020$), irrespective of the block condition (interaction term: no significant cluster). Interestingly, this effect peaks at 180 ms after action-effect onset, that is, shortly before the actual peak of the N1 and, as discussed later, inspection of the grand average ERPs suggests that also the preceding P1 is affected here. This is why we subsequently refer to this negativity on compatible trials as an P1/N1 effect. Overall, there was no difference between high-compatible and high-incompatible blocks.

Difference waves on the P3a (see Figure 5), however, only show a significant cluster on the interaction term from 340 to 410 ms ($p = .027$). A strong positivity is associated with incompatible trials only in high-compatible blocks, as demonstrated by a significant cluster from 330 to 400 ms ($p = .026$), whereas no such effect was observed in high-incompatible blocks. Again, neither an overall difference between high-compatible and high-incompatible blocks nor a difference between current compatible versus incompatible trials emerged.

Discussion

In Experiment 2, we largely replicated the behavioral results of Experiment 1 in a slightly adjusted, EEG-friendly experimental design. In the high-compatible blocks, there is still a significant difference between processing of (currently) compatible and incompatible effects that can be measured in terms of a Task 2 delay. Long-term and short-term R-E links play in concert here and render monitoring of expected compatible effects fastest at the expense of unexpected incompatible effects that take longest to be monitored. In the mainly incompatible setting, however, no such

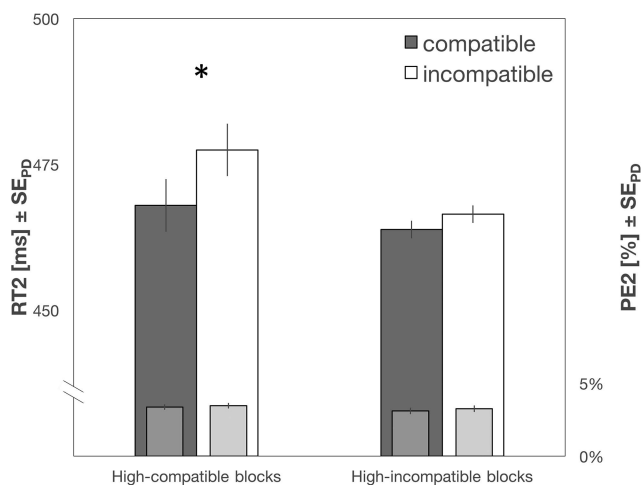


Figure 3. Behavioral results of Experiment 2. Response times (RT2) and percentage of errors (PE2) for Task 2, separately for high-compatible and high-incompatible blocks. Gray bars represent trials that presented a spatially compatible effect in Task 1, white bars represent trials with an incompatible effect. Error bars denote the standard error of paired differences, computed separately for each comparison of compatibility (Pfister & Janczyk, 2013). * $p < .050$.

³ To provide the best possible estimate for the critical interaction, we pooled the data from Experiments 1 and 2 and analyzed RT2 and error rates of Task 2 via a post hoc $2 \times 2 \times 2$ ANOVA with current R-E compatibility (compatible effect vs. incompatible effect), block condition (high-compatible block vs. high-incompatible block) as within-subjects factors and Experiment (1 vs. 2) as a between-subjects factor. Note that this analysis only considers the factors that were manipulated in both experiments, neglecting the factors S2 quality (from Experiment 1) and RSOA (from Experiment 2). This is justified, as both these factors produced main effects without interacting with any of the factors involved in the critical interaction in the separate analyses. Further, we collapsed across experiments that employ different proportions of dual-task trials.

There was a significant main effect of current compatibility for RT2, $F(1, 74) = 9.24$, $p = .003$, $\eta_p^2 = .11$, with faster responses after a compatible (472 ms) than after an incompatible effect (478 ms). The interaction between block condition and current compatibility was significant, $F(1, 74) = 12.06$, $p = .001$, $\eta_p^2 = .14$, with a compatibility effect in high-compatible blocks ($\Delta = 12$ ms, $t(75) = 4.23$, $p < .001$, $d = 0.49$) and no effect in high-incompatible blocks ($\Delta = -1$ ms, $t(75) = -0.52$, $p = .608$, $d = -0.05$). Neither the main effect of Experiment, $F < 1$, nor any of the other effects reached significance, $F_s < 2.12$, $p_s > .149$. Indeed, Task 2 responses were delayed after incompatible effects relative to after compatible effects only when long-term and short-term links matched, whereas no such a delay was found when both kinds of links made opposite predictions. In the error rates of Task 2, neither the main effects nor the interactions were significant, $F_s < 2.12$, $p_s > .150$.

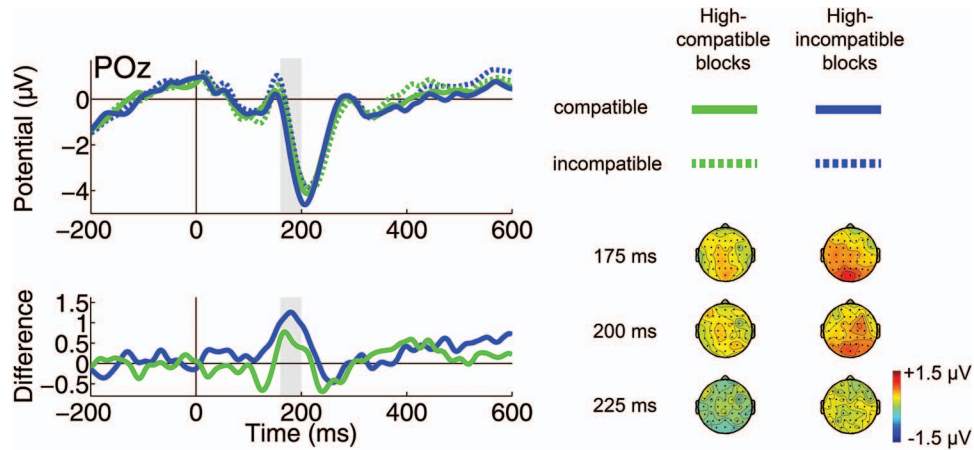


Figure 4. Grand average ERPs at electrode POz (P1/N1). Top left: Grand average ERPs. Bottom left: Difference waves of current incompatible minus current compatible trials in high-compatible blocks (green [light gray]) and high-incompatible blocks (blue [dark gray]). Bottom right: Scalp topographies of these difference waves. See the online article for the color version of this figure.

difference emerges, as long-term and short-term links now suggest divergent predictions that either cancel each other out or abolish any prediction at all, thereby assimilating the monitoring effort of expected incompatible and unexpected compatible effects.

Further, the absent interaction between current compatibility and RSOA in Task 2 lets us gauge the duration of the effect monitoring process more precisely. As of now, we know that the process for monitoring incompatible effects must last at least 50 ms after the response, otherwise there would be no overlap between effect monitoring and processing of Task 2, and no interference should be found. If it lasted until about 50–150 ms after R1, then we should have observed an interaction between current compatibility and RSOA because only for the short RSOA of 50 ms there should be overlap between Task 1 effect monitoring and Task 2 processing, which should emerge in the observed interference. In contrast, interference for the long RSOA of 150 ms, no

such overlap should exist and consequently no interference should be observed. However, we observed that the effect of compatibility propagates to Task 2 equally strong in both RSOA conditions, which is in line with the idea that effect monitoring lasts at least until 150 ms after the response, so that the difference in duration of monitoring compatible versus incompatible effects can fully propagate even with the long RSOA (for a more thorough manipulation of the factor RSOA in a similar setup, see Wirth et al., 2017, Exp. 4).

Overall, we could show that spatial action effect compatibility affects the amplitudes of the visual P1/N1 and the P3a with different characteristics, suggesting separate stages of effect monitoring. Early correlates of visual attention were affected by the current compatibility of the action effect, independent of whether compatible effects were frequent or infrequent in the respective

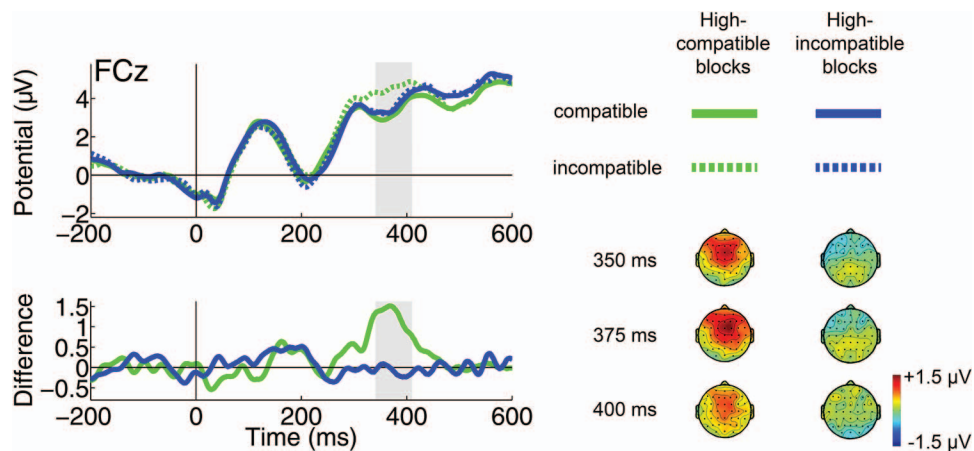


Figure 5. Grand average ERPs at electrode FCz (P3a). Top left: Grand average ERPs. Bottom left: Difference waves of current incompatible minus current compatible trials in high-compatible blocks (green [light gray]) and high-incompatible blocks (blue [dark gray]). Bottom right: Scalp topographies of these difference waves. See the online article for the color version of this figure.

block. As this modulation peaked slightly before the N1 and also affected the preceding P1, two interpretations are possible that lead to the same overarching conclusion. The N1 represents most likely enhanced processing of a target stimulus at the attended location (Hillyard, Vogel, & Luck, 1998; Luck & Hillyard, 1995; Mangun & Hillyard, 1991), and can be interpreted as being increased after compatible action effects. Tying in with N1 findings on stimuli at unexpected locations in variants of the Posner cuing task (Luck et al., 1994; Mangun & Hillyard, 1991), spatially compatible action effects would seem to elicit a larger visual N1 because they appear at the location that has been attended to already before stimulus onset. On the other hand, based on a P1 effect this would have to be interpreted as a reduction and thus a suppression of attention in compatible effects. This is in line with studies on sensory attenuation of self-initiated events (Blakemore, Wolpert, & Frith, 1998; Hughes & Waszak, 2011). For example in the auditory domain, Baess and colleagues (Baess, Horváth, Jacobsen, & Schröger, 2011) reported a reduced frontal N1 in expected self-initiated sounds compared to unexpected externally initiated sounds. This would mean that in the present experiment, the P1 would be reduced after compatible effects because this action-effect link is the employed one and requires attenuation so that it can be distinguished from more relevant externally driven effects (see also Miall & Wolpert, 1996). Importantly, both accounts—increased N1 and reduced P1 – equally refer to early sensory-attentional processes. The fact that this relationship is not inverted in high-incompatible blocks, that is, incompatible action effects do not elicit a different modulation of the P1/N1 when they are more likely to occur, provides evidence that early sensory-attentional processes are based on long-term action-effect links and not on short-term links.

However, in the later stage of effect monitoring that is reflected by the P3a, differences with regard to short-term links about action effects are indeed reflected in P3a amplitudes. The difference between compatible and incompatible effects, with incompatible effects being associated with a larger P3a, can only be detected in high-compatible blocks. In contrast, this difference appears to be completely absent in high-incompatible blocks. This shows that the mere novelty of the more infrequent action effect (as is the case in standard oddball experiments) cannot be the only process at work: although incompatible effects in high-compatible blocks were just as infrequent as compatible effects in high-incompatible blocks, the later ones did not show any deviations from the more frequent condition. This pattern mirrors exactly the behavioral results of effect monitoring on Task 2 RTs in Experiments 1 and 2, which suggests that the observed delays in Task 2 processing are linked to this stage of effect monitoring.

As expected, there was no parietal P3b visible in our data. This corresponds to the fact that the action effects in our paradigm were of no value with regard to task execution and response initiation and a mere “byproduct” that shares similarities with compelling, infrequent distractors in three-stimulus variants of the oddball task (e.g., Jeon & Polich, 2001). Therefore, an attention-based P3a is elicited, whereas task-related updating of working memory, an established functional interpretation of the P3b (Pfister et al., 2016; Polich, 2007; Polich & Criado, 2006), is omitted.

General Discussion

With the present experiments, we tested how the proportion of spatially compatible and incompatible action effects in a given block and the current compatibility of such action effects in a given trial of a Task 1 shape performance in a subsequent classification task (Task 2). We assume that the impact of Task 1 on the subsequent Task 2 suggests that action effects produced by Task 1 continue to be monitored.

Behavioral Results

In the behavioral data, we observed that it takes less time to monitor compatible compared to incompatible effects, even when the R-E compatibility was unpredictable (Exp. 1, random blocks; see also Wirth et al., 2017 Exp. 5a & 5b). Conceivably, this observation reflects long-term R-E links established prior to the experiment, as usually agents produce feedback (tactile, proprioceptive, visual, auditory) that is spatially compatible to the action itself.

However, when participants encounter situations in which the R-E relations are predictable (high-compatible and high-incompatible blocks), short-term links can evolve as well. In this case, long-term as well as short-term links apparently affect the effect monitoring process concurrently: Long-term links overall still favor spatially compatible effects, even more so when accompanied by corresponding short-term links (in case of a high-compatible block). However, when compatible effects are rare and incompatible effects are frequent, long-term and short-term links run into opposition, and seem to cancel out their behavioral impacts, or abolish predictions about the upcoming effects altogether. Finally, when action effects are both unexpected and incompatible, Task 2 responses are delayed the most, most likely reflecting that monitoring such effects takes longest.

Electrophysiological Results

The ERP data corroborate the aforementioned data patterns. The visual P1/N1 as correlates of early sensory-attentional processes are sensitive only to current compatibility, with a modulation irrespective of the overall compatibility proportion. Following our initial logic, the P1/N1 seem to engage long-term R-E links. In contrast, the P3a is sensitive to both, the spatial compatibility in a trial, and the relative probability of compatible events in a block. Conceivably, the mechanism underlying the P3a integrates both long-term and short-term links, resulting in an enhanced amplitude only when both kinds of links are violated (as with unexpected incompatible effects in the high-compatible setting). Further in line with the fact that the action effects in our design were completely irrelevant for any subsequent action, the parietal P3b activity was completely absent after action effect onset (Polich, 2007; Polich & Criado, 2006).

Whereas the behavioral data suggest *that* short-term and long-term links operate concurrently, with an overt button press as the final output of this joint impact, the action effect-locked ERPs suggest a more fine-grained picture of *when* these influences occur. Long-term links seem to manifest their influence early at the visual N1; therefore, they seem to be constantly activated, and consequently shape our behavior from the earliest point, even when they provide no benefit (cf. Exp. 1, random blocks). Short-term links seem to manifest in the P3a somewhat later (between

~200–400 ms after the effect onset), where both links have already worked concurrently. At both instances, the duration of the effect monitoring stage is affected, so that subsequent responses are postponed (a) after incompatible effects (due to long-term links), and (b) after unexpected effects (due to short-term links), which culminates in the longest postponement for (a + b) unexpected, incompatible effects.

Additive Canceling Versus No Prediction

However, it remains unclear whether there are really two separate types of links (long-term and short-term) that are integrated and cancel each other out in terms of opposing predictions, or whether humans only acquire links based on their long-term experience and express expectations about the upcoming effects only when the current situation reinforces these links. Both models would produce the data pattern that we obtained in Experiment 1 (and found descriptively in Experiment 2, see also Footnote 3), so empirically we cannot differentiate between these two options.

It is debatable which of these two models is more viable and parsimonious. Additive cancelling assumes that there are two types of links that are always present and are combined to predict the upcoming sensory changes in the environment based on an action. The no prediction model simply assumes that there are only long-term links, but these are only used for prediction if the experience of interacting with the current setting does not violate those long-term links too often. This question could be addressed by a more granular manipulation of the ratio between compatible and incompatible trials within a block. Where the additive cancelling model would predict that with an increasing ratio of incompatible trials, the burdens of monitoring incompatible trials should shrink gradually, the no prediction account would assume that as long as long-term expectations are met by the current setup (with more than 50% compatible trials), the difficulty to monitor incompatible effects should be approximately equal.

Finally, it needs to be studied in more detail, how much experience is eventually needed to create a new or alter an existing action-effect link. Several studies found that even a single encounter of an action-effect coincidence might already establish such a link (Dutzi & Hommel, 2009; Moeller, Pfister, Kunde, & Frings, 2016). However, at present it is not clear whether such single instances reflect the “micro-genesis” of more longer-lasting action-effect links (see also Herwig & Waszak, 2012).

Conclusion

We conclude that, depending on the situational demands, effect monitoring adapts flexibly: With mainly compatible effects, the infrequent incompatible effects lead to a delay in Task 2 responses, whereas infrequent compatible effects with mainly incompatible effects do not slow down Task 2.

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Received January 30, 2017

Revision received November 29, 2017

Accepted December 1, 2017 ■