

Action-effect negativity: Irrelevant action effects are monitored like relevant feedback

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ABSTRACT

Goal-directed action presupposes the previous integration of actions and their perceptual consequences (action-effect binding). One function of action-effect bindings is to select actions by anticipating their consequences. Another, not yet well understood function is the prediction of action-contingent feedback. We used a probabilistic learning task and ERP analyses to compare the processing of explicit, performance-related feedback with the processing of task-irrelevant response-contingent stimuli. Replicating earlier findings, we found that negative performance feedback produced a feedback-related negativity (N_{FB}), presumably related to response outcome evaluation. Interestingly, low-probability but task-irrelevant action effects elicited a signal similar to the N_{FB}, even though it had a shorter duration. Response delays on trials following negative feedback and following low-probability action effects were correlated with one another. These observations suggest that automatically acquired action-effect relations are exploited for anticipating upcoming events. Like task-relevant performance feedback, task-irrelevant action effects serve as a basis for action monitoring processes, presumably mediated by medial frontal cortex.

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1. Introduction

Human action is goal-directed and thus likely to be driven by anticipations of the intended action effects (e.g., rewards or other incentives that are worth the effort). Anticipated action effects can be assumed to subservise at least two important processes in action control: to allow for the selection of actions that are suitable to generate the consequences the agent is interested in (action selection: e.g., [Elsner and Hommel, 2001](#)) and to represent the intended outcome of an action against which the actual outcome can be compared (action monitoring/evaluation: e.g., [Blakemore et al., 1999](#)). Adaptive action control thus requires the acquisition of knowledge about the relationship between actions and their consequences.

2. Action-effect integration

Actions and their effects are thought to be integrated into what one may call *action concepts* ([Hommel, 1997](#)) as a result of frequent

co-occurrence, presumably through some kind of Hebbian learning process ([Elsner and Hommel, 2001, 2004](#)). As a consequence, neural representations of actions and effects become associated in a bidirectional fashion, so that activation between representations can spread in two directions. For one, this allows for the intentional selection of actions as envisioned by ideomotor theory ([Hommel et al., 2001](#); [James, 1890](#); [Lotze, 1852](#)): “thinking of” the intended action consequences (i.e., endogenously activating the codes of the intended action effect) primes and selects the associated action. In fact, neuroimaging studies have shown that presenting a familiar action effect activates brain areas associated with episodic memory and response selection ([Elsner et al., 2002](#); [Melcher et al., 2008](#)). For another, bidirectional action-effect associations support action monitoring ([Hommel, 1998](#)): activating the representation of a particular action spreads activation to the representations of its effects, which amounts to anticipating or predicting them (e.g., [Blakemore et al., 1999](#)). For example, in experienced piano players, depressing a particular piano key will induce the anticipation of the tone by priming the action-tone representation, and this will help to detect errors rapidly.

While the role of action-effect bindings in action *selection* is widely supported, the role in action *monitoring* is still largely unexplored. If representations of action effects are involved in

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action monitoring, one would expect that the processing of action-effect information is similar to the processing of other types of action feedback. This expectation was tested with behavioral measures and event-related potentials (ERPs).

Note that even though we often contrast “feedback” with “action effects” in the present paper, this is not to say that feedback is not an action effect or that action effects cannot provide feedback. The main distinction we intend to draw is between information about an action that is relevant for the given task and the target of optimization processes, and therefore presumably attended and explicitly represented (this is what we in the present context call “feedback”) and other action-contingent information that is not relevant for the task, presumably not considered for strategic optimization, and probably not attended or explicitly represented (this is what we call “action effects”).

3. Action monitoring and feedback processing

3.1. Feedback-related negativity

Numerous studies support the idea that the brain has a dedicated mechanism for monitoring performance: people often detect their own errors and correct them immediately (e.g., Band and Kok, 2000; Rabbitt, 1968; Yeung et al., 2004), and tend to be more cautious in trials following an error (e.g., Band and Kok, 2000; Rabbitt, 1968; Ridderinkhof, 2002; Smith and Brewer, 1995). For a more direct indication, ERPs synchronized to the onset of an incorrect response show a negative deflection relative to correct trials, a component known as the error negativity (N_E ; Falkenstein et al., 1990) or error-related negativity (ERN; Gehring et al., 1993). The N_E /ERN immediately follows the response and is usually largest over fronto-central scalp locations. The functional interpretation of the N_E /ERN has developed over the years since its first discovery because other events than overt errors also elicit a component similar to the N_E /ERN. A broader interpretation of these waveforms is in terms of conflict monitoring, which is assumed to form the basis for detecting both errors and risk of errors (Yeung et al., 2004).

The interpretation of the N_E /ERN reflecting performance monitoring processes is further supported by the observation of a very similar ERP component after participants receive feedback about their performance (Miltner et al., 1997): ERPs go more negative over fronto-central midline brain areas, between 200 and 400 ms following negative as compared to positive feedback, regardless of whether performance was actually incorrect. This waveform has been dubbed the feedback-related negativity (N_{FB}). We will adopt this name as a non-theoretical descriptive label for the negativity following feedback. The relationship between N_E /ERN and N_{FB} has been elucidated by Holroyd and Coles (2002), who varied the validity of performance feedback in a probabilistic feedback study. N_E /ERN and N_{FB} were both sensitive to the valence of the eliciting event as well as its information value, i.e., whether the event clarified whether an error was made. Based on these and other findings, Holroyd and Coles (2002) presented a unified account for the N_E /ERN and N_{FB} . They argued that these components reflect the transmission of a negative reinforcement signal from the mesencephalic dopamine system to the ACC, which in turn initiates adaptive processes that affect the probability of giving a specific response to a stimulus. Accordingly, the system responsible for the N_E /ERN and N_{FB} is involved in reinforcement learning: stimulus–response (S–R) combinations leading to unexpected absence of reward lose associative strength, whereas combinations leading to unexpected reward gain associative strength. Consistent with this approach, source analyses and imaging studies have indicated that the same part of the ACC is responsible for both the N_E /ERN and N_{FB} component (Holroyd et al., 2004; Miltner et al., 1997) and a meta-analysis of studies on performance monitoring in humans and other

primates found sources of activity scattered over the medio-frontal cortex (MFC), with the highest density of estimated sources in the rostral cingulate zone (Ridderinkhof et al., 2004).

Several studies have recently tried to link the N_E /ERN or N_{FB} with components in the N2 family with a maximum amplitude over the fronto-central cortex (e.g., Folstein and Van Petten, 2008; Nieuwenhuis et al., 2003; Yeung et al., 2004). The control-related N2 is sensitive to the presence of conflicting response tendencies and the requirement to suppress incorrect responses. Some have argued that this component reflects the same process as the N_E /ERN and N_{FB} , but that the timing varies depending on when the participant finds out whether the response tendency was correct (e.g., Nieuwenhuis et al., 2003; Yeung et al., 2004).

Alternatively, it has been argued that the N_{FB} may actually be an *oddball* N2, a negative waveform that is larger on low-probability than high-probability stimuli (Holroyd, 2004), even if the probability refers to an endogenously anticipated stimulus rather than the actual frequency of a stimulus throughout an experiment (Folstein and Van Petten, 2008). Holroyd et al. (2008) performed principle components analysis on the ERPs of an oddball task and a task with feedback and found that the ERP difference following negative versus positive feedback is not caused by differences in the N2, but by differences in an overlapping positive waveform.

Regardless of the way the N_{FB} can best be classified, the current study is aimed at testing whether irrelevant low-probability action effects, as compared to high-probability action effects, elicit an action-effect negativity (N_{AE}) with the same properties as the N_{FB} . It is hypothesized that a low-probability action effect, because it does not match a learned association, signals that a different action than planned may have been performed. Therefore, it will rapidly trigger medio-frontal cortex activity associated with performance monitoring, which will be visible in a negative potential difference compared to a high-probability action effect.

3.2. Feedback-related positivity

Response-feedback does not only induce an N_{FB} but also a positive deflection relative to correct trials around 300–600 ms after the feedback, with a centro-parietal maximum. The interpretation of this component is still preliminary, but it has been argued that unexpected feedback is a rare event and evokes a P3b (Overbeek et al., 2005). In the current study feedback, action effects, or both may elicit a positive waveform (non-theoretically labeled as P_{FB} and P_{AE}). It is hypothesized that low-probability action effects, because they are irrelevant for the task at hand and may even escape awareness, will not evoke a P_{AE} , whereas relevant negative feedback will evoke a P_{FB} .

4. Present study

Can low-probability action effects that are task-irrelevant and thus unlikely to be attended evoke ERP components that are comparable to those reported in studies of intentional feedback processing? We tested this by recording ERPs for both stimulus events in the same experiment. To assess the processing of negative feedback, we included a standard manipulation that is known to produce an N_{FB} —a slightly adjusted version of the probabilistic learning task used by Holroyd and Coles (2002). Our participants had to classify visual stimuli by speeded two-choice responses and the correct stimulus–response mapping had to be discovered by using the negative or positive feedback. Positive feedback was associated with a monetary bonus and negative feedback was associated with monetary loss. The validity of the feedback was fixed at 80%. In line with previous studies, the prediction was that negative, as compared to positive feedback evokes an N_{FB} and possibly a P_{FB} .

The theoretically more interesting manipulation was that each key press produced a task-irrelevant but action-contingent tone—the events that we call “action effects”. Numerous ideomotor studies have shown that this kind of manipulation is sufficient to acquire bidirectional associations between the key press and the tone representations, provided that the delay between the key press and the tone is not too long (about 1 s or less) and the key-tone contingency is nonrandom (e.g., [Elsner and Hommel, 2001, 2004; Hommel and Elsner, 2000](#)).

We used action effects that were entirely irrelevant for the classification of visual stimuli. They consisted of vowel sounds that were triggered by pressing a particular key. Within each block of trials one of the two responses was followed by one vowel on 80% and by another vowel on 20% of the trials, thus creating one dominant action-effect association for this key and making the irrelevant action effect relatively predictable. The other response was followed by four possible vowels, occurring with frequencies of 40%, 40%, 10%, and 10%, thus making the action effect of this key virtually unpredictable. The unpredictable conditions served mainly as filler conditions to allow presenting all action effects with the same probability across the experiment and to keep the overall predictability of action effects at a minimum. The main interest was in the contrast between the conditions with high-probability (80%) and low-probability (20%) action effects.

If our assumption is correct that irrelevant action effects are processed the same way as task-relevant, attended feedback, we would expect that a low-probability action effect produces an N_{AE} comparable to the N_{FB} that can be observed for negative feedback. Some evidence that acquired action effects can modulate ERP components has been provided by [Waszak and Herwig \(2007\)](#). Their participants acquired associations between left and right key presses and tones of different pitch before participating in an auditory oddball task (with numerous standards and infrequent deviants). Auditory deviants produced a P3 that was more pronounced when it was preceded by the response that was associated with the standard, suggesting that action-tone associations affected tone processing. The observation of an N_{AE} in the current study would support the idea of a shared mechanism for the evaluation of both action-relevant and merely incidental consequences of an action and would suggest interesting theoretical connections between views on reinforcement learning and on ideomotor action control. In contrast, we assume that negative feedback, which in our study needed to be consciously monitored, might evoke a P_{FB} . However, because action effects were not relevant for the classification task and were not likely to be attended, no P_{AE} was predicted to occur in response to low-probability action effects.

Observing an N_{FB} after irrelevant but deviant action effects would have theoretical implications, not only for the role of action effects in performance monitoring, but also for the functional interpretation of the N_{FB} . In particular, current theories of the N_{FB} implicitly assume that the eliciting stimuli are all task relevant (see e.g., [Ridderinkhof et al., 2007](#) for a review). In particular, all models of the N_{E}/ERN and N_{FB} consider the role that the current outcome of an action has in attaining the current goal. If the current study would show an N_{AE} on irrelevant action outcomes, this would point at a more generic role of the MFC in deviance detection, of which response conflict, overt errors, unfavorable feedback, and perceived risk of errors would be the cases already known, and possibly also the more salient ones.

5. Method

5.1. Participants

Eleven female and eight male students from Leiden University participated in the experiment. The age range was 18–25 years ($M = 21$) and three participants were left handed. They were paid € 12 or course credit for participating in the 2-h experiment and could earn a monetary bonus up to € 5 for high accuracy ($M = €$

3.08). Three more participants were excluded from subsequent analyses because they had earned a negative bonus, suggesting that either they did not understand the instructions or did not put enough effort in the task. The experiment was conducted in accordance with relevant laws and institutional guidelines and was approved by the local ethics committee from the Faculty of Social Sciences. All students read and signed informed consent.

5.2. Stimuli and apparatus

Participants sat in front of a monitor in a dimly lit, sound-attenuated room. Visual stimuli were presented on a 19 in. CRT monitor. Auditory stimuli were presented through Etymotic[®] air pulse ear phones. Responses were recorded with keys mounted on the armrests below the index and middle finger of both hands.

Experimental trials started with the presentation of a fixation cross during 500 ms. Next, a random choice out of two visual stimuli from the Snodgrass standardized set ([Snodgrass and Vanderwart, 1980](#)) was presented as a black line drawing on a white background. The image subtended a visual angle of about 2°. These imperative stimuli required a speeded response with the index or middle finger of the same hand. If a key press was made within 800 ms, it was followed after 14 ms by an auditory stimulus of 270 ms duration and an intensity of approximately 70 dB. During response omissions no sound was presented. Following the auditory stimulus the visual stimulus remained on the screen for 930 ms after which the fixation cross for the next trial was presented.

The auditory stimulus was a merger of an action effect and a feedback element. The action-effect element was one of four different Japanese vowels /æ/, /i:/, /o/, and /a/ (<http://www.ymec.com/hp/signal2/voice5.htm>). These action-effect stimuli will be referred to as E1, E2, E3, and E4. The contingency of E1–E4 on the use of the four response buttons is clarified in [Fig. 1](#) for one of the balancing conditions. Of the four response buttons (R1–R4), R1 presses were unpredictably followed by E1 on 80% and E2 on 20% of the trials. R4 (right middle finger) was mapped in the same way to E3 and E4. To provide an equal distribution of action effects, R2 and R3-presses (left and right index fingers) were associated with all possible action effects, with E1 and E3 presented in 10% of the trials, and E2 and E4 in 40% of the trials. This procedure was chosen so that even in the unlikely situation that participant would figure out the contingency they would be able to predict the action effect correct on only 60% of the trials. This was meant to contribute to the overall experience that action effects were not predictable, despite the fact that in the 80%/20% conditions they were more predictable. The procedure also ensured that each action effect occurred with the same probability throughout the session.

The feedback element in the auditory stimulus consisted of the presence or absence of white noise, indicating a correct or incorrect response with 80% validity. That is, correct responses were followed by positive feedback on 80% and negative feedback in 20% of the trials. After incorrect responses, there was negative feedback on 80% and positive feedback on 20% of the trials. The assignment was balanced across participants, and the action effect and feedback elements varied independently. The negative and positive feedback corresponded to a loss of two cents or a gain of one cent to their bonus. Omissions led to a loss of four cents. Participants began the experiment with a 100 Euro cents bonus. The current bonus score was displayed after each block.

Note that the current design, as most other designs of probabilistic learning studies, actually confounds the validity, predictability, and valence of feedback. This lies in the logic of learning: valid feedback about a correct response is necessarily positive, and making this feedback less predictable necessarily affects the frequency of valid and positive feedback in the context of correct responses. Given that analyses (of RTs and ERPs) are typically restricted to trials with correct responses, some degree of confound is unavoidable and we flagged them in the present paper wherever appropriate. Interestingly, however, the similarity between the effects of positive versus negative feedback (where the confounds are present) and high-probability versus low-probability action effects (where they are not) that we will demonstrate in the following suggests that expectation is actually the most relevant variable.

5.3. Procedure

Participants were familiarized with the auditory stimuli in advance. Noisy and clear feedback sounds were presented before the start of the experiment, and their meaning was explained, including the fact that the feedback signal “was often but not always reliable”. In contrast, the meaning of the different vowels was not explained in advance although participants were instructed to “look for a pattern between responses and subsequent vowels”. This instruction was given to draw the participant’s attention to the vowel sounds at the onset, and thereby trigger at least a minimum amount of vowel processing.¹ However, the instruction was not

¹ Although in most studies integration of actions and effects seems to happen automatically, that is without attention ([Eenshuistra et al., submitted for publication; Hommel et al., 2003; Kunde, 2004](#)), there also seems to be a modulation by the salience of the action effect. [Dutzi and Hommel \(2009\)](#) found that while integration occurs automatically with task-irrelevant auditory action effects, for visual task-irrelevant stimuli to be integrated, they need to be salient. This uncertainty about the automaticity of integration was reason to briefly bring the variability of the vowels to the participants’ attention through an instruction.

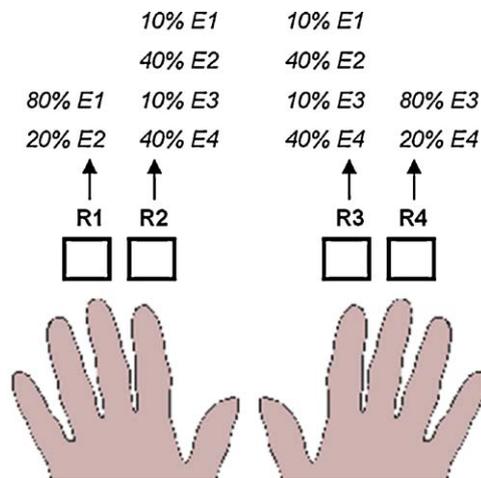


Fig. 1. An example of the response–action–effect mapping as used in this experiment. R1 and R4 were always associated with the middle fingers of the left and right hand. After a particular response button was used, in a random 80% of the trials this was followed by one particular action–effect sound (e.g., /æ/) while infrequently (20%) followed by another sound (e.g., /o/). All four different sounds were associated with buttons R2 and R3 to balance the frequency of different sounds presented to the participant.

repeated or referred to throughout the rest of the session. In response to informal inquiry with the participants following the experiment, none reported any knowledge of the contingencies.

After instructions, 32 blocks of 40 trials each had to be carried out, interrupted by short self-paced breaks. In each block only one hand was used, with left and right hand use alternating each block. On every block, participants were told which hand and buttons to use and were instructed to find the responses belonging to each of the two stimuli used through trial and error, making use of the probabilistic feedback. Each block of 40 trials used two new visual stimuli, which were equiprobable.

5.4. Electrophysiological recordings

Electroencephalographic (EEG) activity was recorded over positions C3, C4, Fz, FCz, Cz, Pz and Oz of the 10/20 standard. Horizontal eye movements were calculated by bipolar derivations of electro-oculogram (EOG) signals over the left and right outer canthus. Vertical eye movements were calculated by bipolar derivations of signals above and below the left eye. Monopolar recordings were referenced to the common mode sensor (CMS) and drift was corrected with a driven right leg (DRL) electrode (for details see <http://www.biosemi.com/faq/cms&drl.htm>). In order to re-reference the data off-line, two baselined EEG data, feedback-locked segments were taken with a window from 1200 ms before to 1000 ms after the feedback, which were later averaged.

5.5. Analysis

Off-line analyses were performed with Brain Vision Analyzer. After re-referencing the channels to the average mastoid, data were smoothed with a high-pass filter of 0.1 Hz and a low-pass filter of 12 Hz (both 24 dB/oct). Correction for ocular artifacts was applied using the standard Gratton et al. (1983) method. EEG and EOG segments with absolute amplitudes exceeding 1000 μ V, as well as EEG segments with amplitude changes smaller than 0.50 μ V or amplitude changes larger than 100 μ V were rejected as artifacts (10% of the trials). EEG data were first baselined to the mean amplitude in the 200-ms interval prior to the presentation of the imperative stimulus. From these baselined EEG data, feedback-locked segments were taken with a window from 1200 ms before to 1000 ms after the feedback, which were later averaged.

Analyses of the effect of feedback and action effect were performed as analyses of variance (ANOVA) on the mean amplitude of the N_{FB} , N_{AE} and P_{FB} using the factors electrode and signal probability. Greenhouse–Geisser correction was applied to the *dfs*, but original *dfs* are reported.

To calculate the onsets and offsets of the N_{FB} and N_{AE} , the first step in the analysis was to compute two difference waves; one for low-probability versus high-probability action effects, and one for incorrect versus correct feedback. The onsets and offsets in these difference waves were defined as the first and last sample in the first 500 ms following feedback on which the amplitude was more negative than –3 times the SD of the activity in the window preceding the feedback. This was from 173 to 354 ms for N_{FB} and 176 to 234 ms for N_{AE} . Likewise, onsets and offsets of the P_{FB} was defined by as the first and last sample in the window of 300–1000 ms following feedback on which the amplitude was more positive than 3 SD. This was

395–710 ms for P_{FB} . An analogous P_{AE} was not observed. Differences in onsets and offsets were tested using the jackknife-based method proposed by Miller et al. (1998).

6. Results

6.1. Behavioral performance

For reaction time (RT) analyses, trials with button presses preceding the stimulus, $RT > 1000$ or an incorrect response were excluded. Mean RT was 403 ms and mean accuracy was 76.1%. Performance to stimuli and responses associated with an 80%/20% versus a 40%/40%/10%/10% action–effect schedule was compared by means of an ANOVA with the factor action–effect schedule. Unsurprisingly, there were neither effects on RT nor on accuracy, $F_s < 1$, which rules out that the frequency of confirmation of the anticipated action effect as such played a role. Given our interest in the contrast between processes following high-probability versus low-probability action effects under otherwise identical conditions, further analyses were restricted to trials with the 80%/20% action–effect schedule.

If we assume that registering negative feedback or low-probability action effects induces conflict between the codes representing the expected and the actual events, it is possible that this affects subsequent trials. To exclude this possibility, we analyzed only those trials on which both the current and the previous response were correct and from the 80%/20% action–effect schedule, which implies that these were all stimulus repetitions. Mean RT did not differ between trials following negative and positive feedback, $F = 1$. Then, the data were further filtered to include only trials with positive feedback on the previous trial, and the effect of action–effect history was tested. Mean RT was 8 ms longer after low-probability than after high-probability action effects, $F(1,18) = 8.8$, $MSe = 62$, $p < .01$, $\eta_p^2 = 0.329$, which may indeed point to a conflict between (implicitly) expected and actual action effects. Also of interest, the measures of feedback-related and action–effect-related slowing (RT following negative feedback minus RT following positive feedback, and RT following low-probability effects minus RT following high-probability effects) were correlated, $r(19) = 0.52$, $p < .02$.

Analogous analyses were performed on response accuracy. All trial inclusion criteria were the same as for RTs, except for the accuracy of the current response. Accuracy was higher following positive than negative feedback (99.0 vs. 84.3%), $F(1,18) = 117.9$, $MSe = 17.5$, $p < .001$, $\eta_p^2 = 0.868$. Accuracy did not differ between responses following low-probability as compared to high-probability action effects, $F < 1$.

6.2. Event-related potentials

For the N_{FB} component only correct response trials were used, comparing between all positive and negative feedback trials. To investigate ERPs in relation to action effects, the analysis was restricted to responses that were followed by high-probability (80%) or low-probability action effects (20%). Only those trials were included that had a correct response as well as positive feedback.

Fig. 2 (left panel) shows the grand average ERPs on correct trials, following positive and negative feedback. The negative amplitude difference following negative as compared to positive feedback had a diffuse scalp distribution and was largest over Pz, followed by Fz, FCz and Cz. On average, the N_{FB} for these four electrodes exceeded the 3 SD criterion from 173 to 354 ms and peaked at 268 ms following the feedback. An ANOVA of the mean amplitude between 173 and 354 ms, with the factors feedback (negative vs. positive) and electrode (Fz, FCz, Cz, Pz) showed a main effect of feedback, $F(1,18) = 33.3$, $MSe = 3.4$, $p < .001$, $\eta_p^2 = 0.649$, a marginal

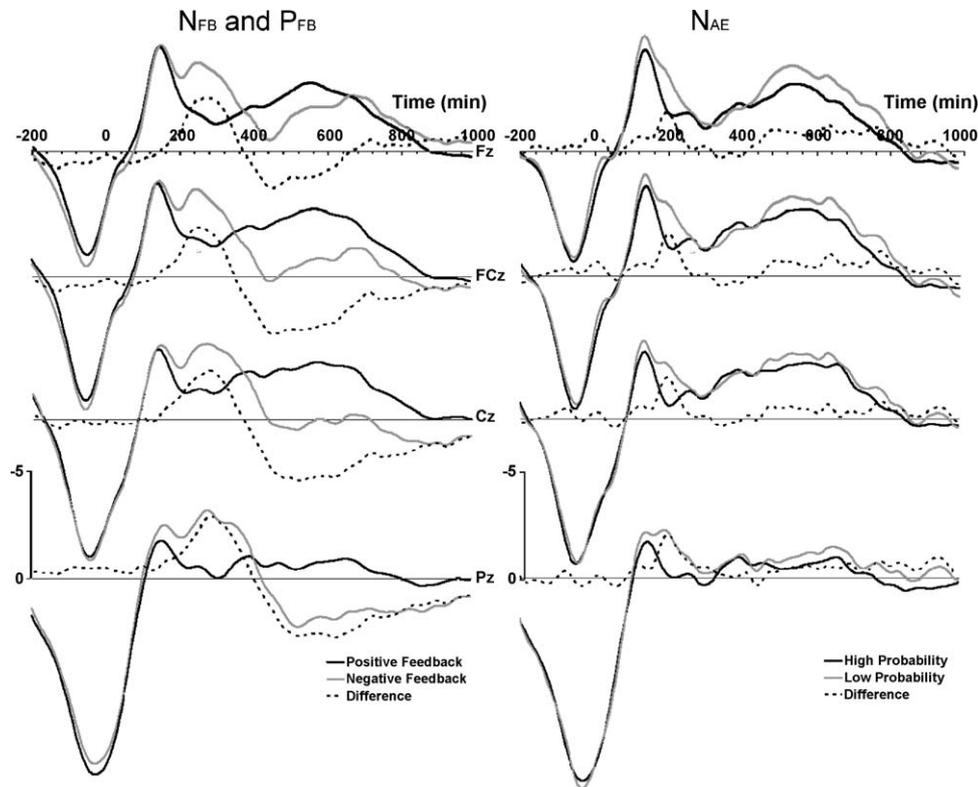


Fig. 2. Average ERPs time-locked to the auditory stimulus (time zero), which immediately followed the response and carried relevant feedback as well as an irrelevant action effect. All ERPs are based on trials with correct responses. Left panel: ERPs to positive and negative feedback and the difference wave. Right panel: ERPs to the high-probability (80%) and low-probability (20%) action effects, and the difference wave.

effect of electrode, $F(3,54) = 2.9$, $MSe = 7.6$, $p < .10$, $\eta_p^2 = 0.138$, and no interaction ($F < 1$).

Fig. 2 (right panel) shows that there was also a negative amplitude difference following trials with low-probability action effects relative to high-probability action effects. This difference had a diffuse scalp distribution and was largest over Pz, followed by Cz and FCz. On average, the N_{AE} for these three electrodes exceeded the 3 SD criterion from 176 to 234 ms and peaked at 201 ms following the feedback. An ANOVA of the mean amplitude between 176 and 234 ms, with the factors action effect (low-probability vs. high-probability) and electrode (Pz, FCz, Cz) showed a main effect of action effect, $F(1,18) = 16.4$, $MSe = 4.4$, $p < .001$, $\eta_p^2 = 0.477$, a marginal effect of electrode, $F(2,36) = 2.7$, $MSe = 8.4$, $p < .10$, $\eta_p^2 = 0.129$, and no interaction ($F < 1$).

Following the N_{FB} , there was a positive amplitude difference on trials following negative relative to positive feedback which we refer to as a P_{FB} . It was largest over Cz, followed by FCz and Pz. It exceeded the 3 SD criterion from 395 to 710 ms for all three electrodes. An ANOVA of the mean amplitude in this window, with the factors feedback and electrode (Cz, FCz, Pz) showed a main effect of feedback, $F(1,18) = 23.0$, $MSe = 5.7$, $p < .001$, $\eta_p^2 = 0.561$, a main effect of electrode, $F(2,36) = 19.8$, $MSe = 3.6$, $p < .001$, $\eta_p^2 = 0.524$, but no interaction of feedback and electrode, $F < 1$. The comparison of low- and high-probability action effects did not reveal a P_{AE} .

6.3. Comparison between negative waveforms

A direct comparison of the negative differences following feedback and action effects consisted of three parts; the amplitude, the timing, and the scalp topography. Mean amplitudes between 176 and 234 ms, the window in which both difference waves were significant, were submitted to an ANOVA with the factors information (feedback vs. action effect), probability (high vs.

low) and electrode (FCz, Cz, Pz). Apart from a first order effect of information, $F(1,18) = 5.1$, $MSe = 2.3$, $p < .05$, $\eta_p^2 = 0.221$, which indicated that the negative peak was larger to relevant feedback than to action effects, there were no effects involving the factor information $F_s < 1$.

The timing of the N_{FB} the N_{AE} was compared using the jackknife procedure (Miller et al., 1998) limited to the Pz. The onset difference between the N_{FB} (148 ms) and the N_{AE} (167 ms) was not significant, $t(18) = 0.3$, $p > .1$, but the offset was later for the N_{FB} (386 ms) than for the N_{AE} (257 ms), $t_{1-tailed}(18) = 1.8$, $p < .05$.

Both difference waves had diffuse scalp topographies, with no significant differences between amplitudes across midline electrodes, so the finding that they both reached a parietal maximum is insufficient support for a topographic similarity of the waves. In fact, given the small differences in amplitude, a voltage map or current-source density map might be misleading. Therefore, the correlation between the mean amplitudes of the two grand average difference waves in the interval 176–234 ms was calculated, using electrodes as cases (cf. Holroyd et al., 2008). The Pearson correlation was $r(7) = .93$, $p < .002$.

Finally, it was tested whether individual differences in the size of the N_{AE} were associated with individual differences in the size of the N_{FB} . For this purpose, mean amplitudes were calculated in the windows with significant activity. The correlation of both amplitudes across participants over Pz was significant, $r(19) = .43$, $p < .05$.

7. Discussion

In this study we used a probabilistic learning task with irrelevant action effects to study possible similarities between the intentional processing of feedback and the automatic processing of action effects. In particular, we were interested to see whether low-probability action-contingent signals would induce

the same ERP components as negative feedback information does. In view of the mean accuracy of about 76%, it seems safe to conclude that our participants were able to use the provided feedback to acquire the appropriate stimulus–response rules and that they were not too much distracted by the manipulation of action–effect contingencies.

Our manipulation of feedback validity replicated previous findings in showing a pronounced N_{FB} for negative feedback over a substantial part of the midline, peaking between 173 and 354 ms after feedback onset (Holroyd and Coles, 2002; Nieuwenhuis et al., 2005). The behavioral data provide evidence that performance in trials following the processing of negative feedback is impaired (in terms of accuracy, not RT). Clearly, the mismatch between expected and actual feedback creates conflict. The presence of conflict has been claimed to trigger conflict–resolution operations, such as updating the task representation (Egner and Hirsch, 2005), which arguably uses up resources that otherwise could be spent on processing the subsequent target. Even though such post-conflict impairments are more commonly reported for RTs than they are for error rates (e.g., Rabbitt, 1968), our observations fit with the general idea that dealing with conflict takes time and resources—be it because of dedicated conflict–resolution processes or simply because the conflict extends into the subsequent trial and increases cognitive noise. In any case, the observed impact of feedback expectancy provides clear evidence for the detection of feedback information that deviates from the expectations.

Particularly interesting for our purposes, violations of expectations related to action effects produced very similar outcomes. First, low-probability action effects also impaired performance in the subsequent trial. Here it was RTs but not error rates that were reliably affected. The significant correlation between feedback- and action-effect-related slowing suggests that the two expectation effects followed similar patterns. Apparently, processing an action effect that does not fit with one's (presumably implicit) expectations induces a conflict similar to what we concluded for the intentional processing of feedback. If so, action effects must have been processed, encoded together with the corresponding response, and stored—as expected from an ideomotor perspective on action control (Elsner and Hommel, 2001; Hommel et al., 2001).

The absence of slowing following negative feedback may be due to S–R relations changing from block to block. As a result, negative and positive feedback were equally informative to the subject in the process of finding out the rules and this may explain why it did not differentially affect response speed on subsequent trials. In contrast, action–effect contingencies remained the same throughout the session, and thereby participants had the chance to develop strong action–effect anticipations. This may explain why low-probability action effects were followed by a change in RT.

Importantly, our findings suggest that even task-irrelevant action–effect representations are used to predict the most likely outcome of a given action and are matched against the actual outcome (Wolpert et al., 1995). This confirms that action effects do not only play a role in action selection, the process most ideomotor theories focus on, but also in action monitoring and/or evaluation. Given that the manipulated action effects were entirely irrelevant for the task at hand, finding evidence for a predictive role of action–effect representations provides support for approaches claiming that the human cognitive system is fundamentally anticipatory and continuously trying to generate the best predictions possible based on the available information (e.g., Neisser, 1974; Schubotz, 2007; Zacks et al., 2007).

A second reason to consider the detection of low-probability action effects and negative feedback equivalent is that both types of violations of expectations evoked a highly similar negative waveform. Both the N_{FB} and the N_{AE} showed a maximum effect over Pz and the topographies of N_{FB} and N_{AE} were highly

correlated. The onset latencies did not differ, but the N_{AE} decayed sooner than the N_{FB} . The amplitude difference of the negative wave elicited by feedback compared to action effects did not interact with electrode or stimulus probability, suggesting that the two waves were equally sensitive to these experimental factors. With regard to the unity of the source, converging evidence might be sought by source localization studies or the combination of EEG and fMRI. Finally, while the similarity in onset, eliciting events and scalp topography already strongly suggests that N_{FB} and N_{AE} were the same component, there was also a significant correlation between individual amplitudes differences in N_{FB} and N_{AE} .

7.1. Comparison between ERP components

A remaining question is whether the N_{FB} and N_{AE} obtained in the current study should be interpreted as N_E /ERNs or, rather as N2s. N2s are fronto-central negativities peaking around 250 ms that show up in several versions (see Folstein and Van Petten, 2008 for a review). The control-related N2, which has been argued to be same as the N_E /ERN (e.g., Nieuwenhuis et al., 2003) follows stimuli that either induce response conflict, or require response inhibition (Folstein and Van Petten, 2008). The N_{FB} and N_{AE} do not seem to be control N2s because this component only occurs if auditory stimuli are very similar (Falkenstein et al., 1995; Nieuwenhuis et al., 2004), which was not the case in the current study. Furthermore, it is difficult to imagine how relevant feedback could give rise to response conflict or why it would trigger inhibition, given that the response is already elicited before the feedback.

It is also unlikely that the N_{FB} and N_{AE} were a version of the mismatch negativity (MMN, Näätänen and Alho, 1997); an auditory oddball N2 (as suggested by Holroyd et al., 2008). The MMN is evoked only if there is a substantial difference between the overall probability of a standard versus a deviant auditory stimulus, which was not the case here because none of the merged sounds was presented more frequently than on 36% of the trials.² In other words, there were more deviant than standard sounds.

Most important, however, the alternative interpretations mentioned here in terms of a link between the N_{AE}/N_{FB} and the N2 would all be consistent with the main idea of this paper that as much as the N_{FB} signifies feedback monitoring, the N_{AE} signifies the monitoring of action effects. That is, action effects can only elicit an oddball N2, a control N2, or a short-lived N_{FB} if the contingency of an action effect on a specific button press is encoded as a template for the upcoming sound, which is the same as monitoring whether the action effect deviates from the expectation. The mismatch between high-probability and actual action effects could only be registered if indeed the brain was able to anticipate on the most likely action effect. In sum, regardless of the exact classification of the N_{AE} , it supports the view that irrelevant action effects play a role in monitoring for potentially erroneous actions.

The observation that the N_{AE} was short-lived in comparison with the N_{FB} might suggest that feedback was processed more elaborately and to a more advanced level than action effects were (see Krigolson and Holroyd, 2007, for a comparable differentiation of error processing levels). The distinction between processing of feedback and action effect information receives further support from the finding that there was a P_{FB} but not an analogous positive peak to low-probability action effects (P_{AE}). Given that the action effects in the present study were irrelevant, this dissociation is in line with our expectations and the idea that a P_{FB} is more tightly

² The highest probability of a particular vowel was 80% in half of the trials and 10% in the other half. This was orthogonally combined with an 80% probability of valid positive feedback. As a result, the highest probability within each block of a specific vowel/noise combination was $(80 + 10)/2 \times 80\% = 36\%$.

related to conscious processes than the N_{FB} . The dissociation may be a manifestation of the relatively early selection of relevant information. Indeed, one may speculate that the longer-lasting the electrophysiological response to unexpected signals the greater their informational value, and vice versa.

7.2. The role of attention

In view of the conclusion that irrelevant action effects were used to support performance monitoring, it might be argued that participants were looking for regularities between button presses and the vowels, either by instruction or by their own initiative. A valid question then is whether this rendered the action effects relevant, and whether they were attended. The primary task for the participant was to make speeded classifications and find out S–R relations on the basis of feedback. The action effect was irrelevant in this regard because it was not part of the speeded task and was useless in finding out S–R relations, but we do not want to argue that participants paid no attention to it. After all, one of the instructions the participants had received at the beginning of the experiment was to look for a pattern. However, it is not very likely that this instruction was held active throughout a 2-h experiment, because it was neither reiterated, nor relevant for the task at hand, nor evaluated. In contrast, correct performance on the probabilistic learning task continuously required maintenance of the goal to monitor relevant feedback and the instruction and outcome were repeated on every block.

The possibility that participants continued to pay attention to the action effects throughout the task was even further reduced by its difficulty. That is, looking for action-effect patterns was not inherently rewarding. When asked after the experiment, most participants reported that they were not aware of any contingency between buttons and sounds. This makes sense because overall the action effects were only 60% predictable. If we consider that even 100% contingency between events can be ignored by about every second participant (Alonso et al., 2006) and that response-feedback contingencies of 70% can go unnoticed entirely (Haruno and Kawato, 2006), it seems safe to conclude that awareness was not a crucial mediator in the present study.

Finally, treating the action effect as relevant would be incompatible with the finding of an N_{AE} without a P_{AE} . As argued above, the P_{FB} could be interpreted as either reflecting the conscious processing or feedback, or as processing of relevant and infrequent information. The absence of a positivity to low-probability action effects, as opposed to the presence of a positivity to feedback indicates that either the action effect did not reach awareness, or was not processed as a relevant stimulus. It is hard to imagine how a goal to look for action-effect contingencies can be maintained as relevant if salient deviations of the action-effect contingency do not reach awareness.

Interestingly, previous research has shown that the acquisition of action-effect associations does not depend on (and may even be hindered by) conscious perception or task relevance of the relationship between actions and effects (Eenshuistra et al., submitted for publication; Hommel et al., 2003; Kunde, 2004; although see Dutzi and Hommel, 2009, for an exception). Indeed, ideomotor theory assumes that the acquisition of action-effect associations precedes and actually enables the performance of outcome-eliciting voluntary action, which implies that the acquisition itself occurs rather automatically (Elsner and Hommel, 2001; Hommel, 1997).

7.3. The functional role of action-effect monitoring

In sum, it is safe to conclude that while action effects were not treated as relevant stimuli, they did play a significant role in monitoring performance. But why would the brain monitor

performance through irrelevant action effects? The most obvious advantage relates to the development of action control. The behavior of newborns and young infants is often driven by stimuli and reflexes, but by systematically exploring their environment and their own body they very soon acquire the ability to carry out goal-directed, intentional actions. A monitoring system that automatically picks up contingencies between involuntary movements and action effects would be of utmost importance in this ongoing struggle for gaining control over one's motor system (Hommel and Elsner, 2009).

But the monitoring of action effects has advantages for the adult as well, especially if action effects provide useful information that is not otherwise available, that is neither through explicit feedback, nor as part of the attended task. For one thing, the short temporal difference between the action and the outcome is beneficial for the associative strength. For another, the information may become evident over time, as an emergent property of memory storage of events, possibly under the restriction that actions and their effects occur close enough in time (Elsner and Hommel, 2001; Hommel, 2005).

What initially seems to be irrelevant information can turn out to be a more useful indicator of performance than the feedback that is provided by the task. Obviously, the usefulness of an action effect in monitoring will become evident most rapidly if it immediately follows the action and comes from the same source as the action, such as when a tennis player hears the sound of poor stroke. In this sense, the current design was a safe choice in providing immediate action effects that were unmistakably triggered by the button press. It is an open question, however, to what extent mismatches in contingencies will also be picked up if actions and their effects are infrequent or remote in space, such as when turning up the home thermostat does not cause the sound of the heating system switching on.

The idea that mismatches between expected and actual action effects drive the monitoring process implies that the nature of the deviating action effect as such is not critical, as long as there is a detectable mismatch from the action effect template. Given a low-probability action effect, no difference is predicted between monitoring processes evoked by familiar versus novel action effects, although obviously, the mismatch with the expected action effect should be sufficiently salient. The distinction that is made is not between one action effect or another, but between presence versus absence of the expected action effect. This assumption is consistent with a dissociation that has been demonstrated to occur following positive versus non-positive feedback (Hajcak et al., 2006; Holroyd et al., 2006): the N_{FB} following neutral feedback is as large as the N_{FB} following negative feedback, in contrast with the view implicit in the traditional reinforcement learning theory of the N_{FB} (Holroyd and Coles, 2002); that the size of the N_{FB} is proportional to the magnitude of negative feedback. Holroyd et al. (2006) concluded from this pattern that feedback evaluation works in a binary manner: the evaluative system either concludes that the goal is achieved (cf. that the action effect is as anticipated, the feedback is positive) or that it is not. Holroyd et al.'s (2006) version of the theory takes into account that a subjective evaluation that the goal is not achieved can cause any deviation from the anticipated outcome to trigger an N_{FB} (see also Hajcak et al., 2006). If the action outcome is worse than anticipated, this triggers a phasic decrease in dopamine that is transferred to the anterior cingulate cortex, which translates it into an N_{FB} . The current study seems to suggest that a similar process may also underlie the N_{AE} .

In sum, our findings are consistent with the prediction from the ideomotor approach to action control that action-contingent signals are automatically integrated with the action they accompany (Elsner and Hommel, 2001). The novel contribution of the present study is that it provides evidence that action-effect

associations do not only play a role in action selection but also in the monitoring of actions. Apparently, these associations give rise to anticipation of task-relevant and irrelevant perceptual consequences of a given action. Mismatches with respect to both types of consequences are detected automatically and result in an N_{AE} , analogous to the N_{FB} . Although more research on this issue is certainly needed, these observations seem to corroborate the idea that performance monitoring does not rely on explicit feedback but can exploit any action-contingent information available—a possibility that seems to go beyond the assumptions of available action-monitoring approaches.

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