The power of prediction:

subjective expectation enables efficient behavior

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Summary

Our ability to form expectations about future events or the results of our own actions is crucial for efficient behavior. While this notion underlies a range of influential theoretical approaches in cognitive psychology, from reinforcement learning to ideo-motor theory, a number of open questions remain. Recent results from neurophysiological and brain imaging studies suggest that conscious intention – or explicit expectation – is nothing more than a by-product of automatic and unconscious activation patterns, without any real impact on behavior. Explicit subjective expectation has been dismissed by many researchers who regard it either an unreliable measure of "true" mental processes, or question its necessity in explaining behavior in general.

In the current work, I focus on the role of explicit subjective expectation and attempt to answer the following questions: (1) Are verbalized predictions a valid indicator of internally generated expectations? (2) Do such expectations really affect action preparation? (3) What are the differences between expectations arising from external or internal sources? Results from the three studies conducted within the scope of this dissertation demonstrate that verbalized predictions are in fact a valid indicator of subjective expectation and are suitable for use in experimental paradigms. Also, subjective expectation cannot be described as a mere by-product of preparation, but instead feeds into preparation and therefore plays a role in action control. Self-generated expectation was shown to involve early attentional and central decision processes to a greater degree than cue-induced expectation. Consequently, self-generated predictions entailed greater behavioral effects not only for stimulus expectations, but also for expectations regarding a task set. Subjective expectation is therefore also elemental in cognitive control.

Zusammenfassung

Unsere Fähigkeit Erwartungen auszubilden über zukünftige Ereignisse oder die Ergebnisse unserer eigenen Handlungen ist von entscheidender Bedeutung für zielgerichtetes Verhalten. Obgleich diese Ansicht einer Reihe von einflussreichen theoretischen Strömungen in der kognitiven Psychologie zugrunde liegt, bleiben bislang wichtige Fragen dazu offen. Jüngere Ergebnisse aus neurophysiologischen und Bildgebungsstudien legen nahe, dass bewusste Ziele – ähnlich expliziter Erwartung – nicht mehr sind als ein Nebenprodukt von automatischen und unbewussten Aktivierungsmustern und keinen echten Einfluss auf Verhalten haben. Explizite subjektive Erwartung wird vielmals abgetan, weil sie kein zuverlässiges Maß „wahrer“ mentaler Prozesse darstelle, oder weil sie nicht notwendig sei, um Verhalten zu erklären.

In der vorliegenden Arbeit beschäftige ich mich mit der Rolle expliziter subjektiver Erwartung und untersuche die folgenden Fragen: (1) Sind verbalisierte Vorhersagen ein valider Indikator für intern generierte Erwartungen? (2) Haben solche Erwartungen tatsächlich einen Einfluss auf Handlungsvorbereitung? (3) Worin besteht der Unterschied zwischen Erwartungen, die auf äußeren oder inneren Quellen beruhen? Die Ergebnisse aus drei Studien, die ich im Rahmen dieser Dissertation durchgeführt habe, belegen, dass verbalisierte Vorhersagen ein valider Indikator von subjektiver Erwartung sind. Subjektive Erwartung kann nicht als ein Nebenprodukt von Handlungsvorbereitung verstanden werden, sondern trägt zu dieser bei und spielt daher eine wichtige Rolle in der Handlungskontrolle. Selbstgenerierte Erwartung beeinflusst gegenüber Cue-induzierter Erwartung verstärkt frühe Aufmerksamkeits- und zentrale Entscheidungsprozesse. Selbstgenerierte Vorhersagen führen zu verstärkten Verhaltenseffekten, und zwar sowohl bei Stimuluserwartungen als auch bei Erwartungen bezüglich einer Aufgabe. Subjektive Erwartung ist demnach auch entscheidend für kognitive Kontrolle.

List of original publications

This doctoral dissertation is based on the following original research articles:

Study I

Umbach, V. J., Schwager, S., Frensch, P. A., & Gaschler, R. (2012). Does explicit expectation really affect preparation? *Frontiers in Psychology*, 3:378

Study II

Kemper, M., **Umbach, V. J.**, Schwager, S., Gaschler, R., Frensch, P. A., & Stürmer, B. (2012). What I say is what I get: stronger effects of self-generated vs. cue-induced expectations in event-related potentials. *Frontiers in Psychology,* 3:562

Study III

Umbach, V. J., Seifert, U., & Schwager, S. (2013). *The impact of self-generated vs. cue-induced expectations on preparation for task sets*. Unpublished manuscript.

1. Introduction

In a soccer match, a goalkeeper facing a penalty kick will usually start moving before the ball is actually played to increase the chances of saving it within the approximate 500 milliseconds it takes to reach the goal line (St. John, 2010). In order to decide which way to dive, the goalkeeper has to have an expectation regarding the direction in which the shot will go. This can be unconscious, for example, the tendency to move to the right under pressure (Roskes et al., 2011). The goalkeeper may also rely on her knowledge of the shooter's past behavior, or may try to read the shooter's motion pattern. The more accurate the goalkeeper's expectation, the higher the chances of beating the odds that favor the shooter at a success rate between 75% and 85% (Bar-Eli & Azar, 2009).

The focus of this work is the role of expectation in action control. Our ability to form expectations about future events or the results of our own actions is crucial for efficient behavior. In the history of psychology, there have been various theoretical approaches emphasizing the importance of expectation in controlling action and learning. In the following paragraphs, I will briefly sketch these broad ideas before outlining the research questions addressed in this work.

The concept that having the idea of an action can translate into the execution of that action was already discussed by William James (1890, p. 492f.): "[...] in perfectly simple voluntary acts there is nothing else, in the mind but the kinœsthetic idea, thus defined, of what the act is to be." This concept was dubbed the ideo-motor principle, but due to its origins in introspective reasoning it was largely neglected after the advent of behaviorist experimental psychology, in which actions were viewed as more or less simple responses controlled by a stimulus (e.g., Thorndike, 1905). To this day, experiments in cognitive psychology often center around manipulating some kind of audio-visual stimulation and measuring some motoric response to that stimulation (often quantified by response times).

However, voluntary actions have received renewed interest with the recent focus on executive functions. Modern theories of action control have revived the ideo-motor principle (e.g., Hommel et al., 2001), stating that "acting without anticipating is impossible" (Kunde, Elsner & Kiesel, 2007, p. 76).

In a different vein, since Ivan Pavlov carried out his first experiments in conditioning in 1901, the concept of associative reinforcement learning has become one of the central ideas in psychology. According to this view, learning consists of the strengthening of associations between stimuli and responses (S-R; Pavlov, 1927). Challenging this view, Tolman (1948) argued that participants in a learning experiment instead acquired expectancies containing predictive relationships between environmental events. Since then, expectancies have become a key part in most modern learning theories (e.g., Rescorla & Wagner, 1972). Learning takes place when an actual outcome differs from an expected one. This discrepancy is commonly called the prediction error, and it is used to update the expectation to more closely resemble environmental probabilities. Such prediction errors have been found to be encoded in dopaminergic activity of midbrain neurons (Schultz et al., 1997). The detection of unexpected events is also thought to trigger strategy optimization (Frensch et al., 2003).

There is an abundance of theoretical accounts and empirical data suggesting that our cognitive system needs to constantly generate predictions to be able to learn and to act (see Bar, 2011, for a recent overview). Without an expectation, the goalkeeper from our example would not be able to initiate a movement in time. The anticipation of where the ball will go and of how she will save it allows her to take the according action. And if she gets it wrong, the disconfirmed expectation will feed into her accumulated experience and enable her to generate a better prediction next time.

2. Research questions

Learning and action rely on expectations continuously generated by our cognitive system. To measure internally generated subjective expectation, it is inevitable to employ some sort of self-report. This in turn builds on the assumption that such verbal reports are based on direct introspective access to mental processes, an assumption that has been fiercely challenged (e.g., Nisbett & Wilson, 1977). Researchers have suggested that conscious intention might be nothing more than an epiphenomenon of preparatory processes in the brain (e.g., Libet et al., 1983). When asking participants for their subjective expectation, they might simply reflect a preparatory state that is not in turn influenced by that expectation. The first aim of this work is therefore to evaluate if verbalized predictions are a valid indicator of internally generated expectations, and if such expectations really affect action preparation.

Because subjective expectation is difficult to assess objectively in an experimental setting, or because they mistrust its validity on principle, researchers interested in effects of expectation often resort to the use of external stimulation to induce expectation experimentally (e.g., Posner & Snyder, 1975). While allowing for a more controlled environment, this approach compromises the core idea of expectation being generated by ourselves. Expectations inserted from the outside by artificial laboratory manipulations such as cueing procedures might have similar properties and effects as self-generated expectations, but this assumption has hardly been tested in psychological research so far. The second aim of this work is therefore to analyze possible differences between expectations arising from external or internal sources.

This thesis consists of three studies that were conducted to address questions left open by previous empirical and theoretical work on the effects and underlying mechanisms of subjective expectation: (1.a) Is subjective expectation more than a byproduct of preparatory processes, i.e. does it actually affect preparation? (1.b) Are verbalized predictions a valid indicator of subjective expectation, i.e. do they conform to other behavioral measures? (2.a) Is self-generated subjective expectation different from externally induced expectation in regard to its impact on preparation? (2.b) Which cognitive processes are differentially influenced by self-generated and cue-induced expectation? (3.a) Does subjective expectation allow for preparation beyond simple stimulus-response connections, e.g. on the more abstract level of task sets? (3.b) Can subjective expectation enable preparation for cognitive conflict, and reduce its detrimental impact on performance?

3. Overview of studies

In the following pages, I will provide an overview of the studies conducted within the scope of this thesis and discuss the results in relation to the questions formulated above. I will draw connections to the relevant literature and place my own research within a larger context. Finally, I will draw conclusions regarding the overarching question about the role of expectation and argue for the use of explicit subjective measures in this field of research.

3.1. Study I: Does explicit expectation really affect preparation? (Umbach et al., 2012)

The first study was conducted to answer the question whether explicit expectation is more than a by-product of action preparation. Intuitively, we might take for granted the notion that expectation affects preparation. But this notion has been challenged by findings showing that explicit intentions to act only emerge several seconds after the according preparatory processes are initiated in the brain (Soon et al., 2008). What introspectively seems to drive our actions might be nothing more than an epiphenomenon of unconscious processes determined by our brain long before, according to this line of reasoning.

To test whether explicit expectation can actually affect our actions, it is necessary to separate it from preparation. In this study, we manipulated expectation by varying stimulus frequency, and we manipulated preparation by instruction. The frequency manipulation rests on the finding that expectations often originate from our experience: we expect events occurring with a high frequency in the past to be more likely to occur again in the future. Event frequency is also known to influence performance: responses to a more common event are usually quicker than to a rare event. In this way, expectation and performance often go along with each other. Possible causal relations between them are therefore difficult to assess.

With this goal in mind, we developed an experimental paradigm in which participants were led to expect one type of event (the most frequent stimulus), while an additional task demand required them to prepare for a different event (the less frequent stimulus). This additional task demand was reinforced by a severe time constraint: participants were exposed to an unpleasant sound if they did not respond to the less frequent stimulus quick enough. Expectations – in the form of trial-by-trial predictions – did indeed conform to the actual variations in stimulus frequency soon enough. Preparation, and response times, followed along initially, with the fastest responses to the most frequent stimulus. When the additional task demand was introduced, participants immediately adhered to it and gave their fastest responses to the less frequent stimulus in order to avoid the deadline "punishment". While they now consistently responded the quickest to the less frequent stimulus, indicating an increased preparation of that response, their expectation pattern remained unchanged. Participants realized that another stimulus was (still) more frequent and predicted it accordingly. This finding shows that while expectation and preparation *can* go along, and often do, they can also diverge. This makes it implausible to think of explicit expectation as a mere side-effect, or epiphenomenon, of already ongoing preparatory processes. People can seemingly expect one thing and prepare for another.

Given this finding, what is the role of expectation in action control? Do people even use it to prepare for action? To answer this question, we compared trials in which the imperative stimulus matched the participants' prediction with trials in which their predictions were not confirmed. Indeed, participants were able to respond much faster to a correctly predicted stimulus. Interestingly, this was the case for all stimulus frequencies: even with highly infrequent stimuli, participants relied on their prediction and suffered substantial performance costs if their expectation was disappointed. From this finding follows that verbalized predictions are indeed a valid indicator of subjective expectation. And while expectation doesn't necessarily equal preparation, the former can effectively feed into the latter. This is not to say that preparation is solely determined by expectation. As Miller & Anbar (1981) pointed out, frequency effects on response times can arise along two routes: by subjective expectation and by strengthening S-R associations. Our findings are compatible with such an integrative account of associative as well as expectation-based action preparation. While associative mechanisms are better studied and understood, expectation as a source of preparation and a key "player" in action control is only slowly receiving the scientific attention it deserves.

In addition to past experience, expectation can also be based on situational cues. The distinction between these two sources of expectation has been largely overlooked in research on expectation effects. In this study, we compared the effects of subjective predictions with those of either informative or non-informative external cues. Subjective verbal predictions entailed the largest effects on response times and retained a significant impact even after the introduction of the additional response deadline. On the other hand, the influence of the non-informative cues was effectively removed by the additional task demand. As the self-generated predictions were equally unreliable, this suggests subjective expectations are preferentially processed and trigger preparation even if task demands favor a different course of action. With informative and reliable cues, a similar pattern emerged: they retained a significant impact in spite of adverse task demands. As Kunde and colleagues (2007) argue, expectation is an integral component of action control. Expectations are always generated and translated into preparation (of perception or action) as this is usually beneficial to optimize behavior in real life. Artificial external cues don't share this processing privilege by default and have to first prove their usefulness (reliability).

The bottom line of the first study is that explicit expectation really does affect preparation. Contrary to the notion of explicit expectation as a mere by-product of preparation (cf. Soon et al., 2008), our findings ascribe it a causal role in controlling behavior. In investigating the cognitive mechanisms underlying action control it is therefore expedient to look at subjective expectation and to include appropriate measures. We found that self-generated trial-by-trial predictions are a valid indicator of subjective expectation and offer a practical solution for measuring this expectation in experimental paradigms. Compared to expectation induced by external cues, expectation self-generated internally appears to possess different properties. A more in-depth analysis of the cognitive processes involved in these two types of expectation is the focus of the following study.

3.2. Study II: Stronger effects of self-generated vs. cue-induced expectations in event-related potentials (Kemper, Umbach et al., 2012)

The goal of the second study was to investigate the differences between self-generated subjective expectation and cue-induced expectation in regard to the impact on preparation. To examine the cognitive processes involved in these two types of expectation, we included event-related brain potentials (ERPs). It has been postulated that anticipating appropriate environmental conditions is fundamental for efficient goal-directed action (e.g., Kunde et al., 2007). Previous studies of anticipation and expectation have mostly exclusively relied on the use of external cues. While this is usually justified with the lack of control over more subjective measures such as self-generated predictions, the presumed equivalence between these two methods cannot be taken for granted. In the only direct comparison reported in the literature, Acosta (1982) found stronger effects of self-generated compared to cue-induced expectations. Our study was aimed to replicate and expand this finding.

Human actions can be driven by intentions (endogenous) or be triggered in response to a stimulus (exogenous). The differentiation between these two "routes to action" is supported by a large body of evidence (Herwig, Prinz & Waszak, 2007). In intentional, goal-directed action, expectation takes a central role in guiding preparatory processes. But how does expectation arise within the cognitive system? In most experimental paradigms, expectation is induced via the use of exogenous cues, rendering the subsequent preparation as reactive. Truly intentional action outside the laboratory, however, more likely relies on self-generated endogenous expectation. In the previous study (Umbach et al., 2012), we have shown that verbalized self-generated predictions are a valid indicator of subjective expectation, and that this expectation assumes a causal role in determining preparation and subsequent behavior. In the second study, we compared self-generated to cue-induced expectation and examined the underlying cognitive processes using electroencephalographic (EEG) measures.

To allow for a direct comparison, we held all factors constant but the source of expectation. Participants either freely generated a prediction or read aloud a cue on each trial, verbalizing the same words in both conditions. There were no differences in the verbalization latencies between predictions and cues, eliminating this factor as a potential confound. Self-generated predictions entailed stronger behavioral effects, with greater benefits in response time for correct predictions and greater costs for misses compared to cues. When the imperative stimulus matched the predicted or cued response – but not the stimulus – there was no performance benefit compared to complete mismatches. This finding suggests that response preparation depends on the imperative stimulus and was not triggered by expectation in this study. The expectation effect must therefore operate on earlier processing stages.

A premotoric locus of the expectation effect was corroborated by our ERP results. A larger effect in the N2 component for self-generated predictions corresponds to the view that these involve endogenous attention processes to a greater degree than cues. The P3 component exhibited a larger amplitude and earlier peak for correct predictions (compared to correct cues), indicating a stronger impact of uncertainty resolution with self-generated predictions. In the lateralized readiness potential (LRP), onsets reflected the behavioral results, with facilitation only for (complete) stimulus matches, but not for (partial) response matches. According to our ERP results, the expectation effect can therefore be attributed to perceptual and/or central parts of the preparation process. Attentional resources pertaining to expected stimulus properties are seemingly allocated to a greater degree following self-generated predictions. Exogenous cues with a similar (low) reliability are processed with much more uncertainty.

In keeping with the distinction between reactive, stimulus-based action and proactive, intention-based action (Herwig, Prinz & Waszak, 2007), the impact of expectation on action preparation might also differ according to its generation. Expectation can arise endogenously within the cognitive system, based on past experience and current goals. It can also be sparked by exogenous cues. While cues can potentially act as rather automatic triggers for a specific expectation (e.g., Bargh & Chartrand, 1999), subjective predictions are generated only intentionally. As such, it seems plausible that participants are more likely to be in an intention-based mode if they generate expectations themselves. Our results indicate that it is necessary to differentiate between self-generated and cue-induced expectations when studying goal-directed action.

In this study we have shown that self-generated expectations differ from cue-induced in a range of premotoric processing stages and result in stronger behavioral effects. Predicting a stimulus intentionally involves more attentional resources and reduces uncertainty to a greater degree compared to reacting to a cue. When a self-generated prediction was met by the imperative stimulus, participants enjoyed larger benefits in response time (compared to a correctly cued stimulus). Our results point to functional differences between endogenous and exogenous sources of expectation. As expectations always pertained to characteristics of the stimulus in the first two studies, we wanted to see whether these differences also hold for expectations on the more abstract level of task sets. This question was the starting point for the next and final study.

3.3. Study III: The impact of self-generated vs. cue-induced expectations on preparation for task sets (Umbach et al., 2013)

The third and final study was conducted to answer the question whether subjective expectation allows for preparation beyond simple stimulus-response connections, for example on the more abstract level of task sets. Furthermore, we were interested in the role of expectation in cognitive conflict: if it enables preparation for a conflicting task, it should be able to reduce its detrimental impact on behavior. In the previous studies described here, expectations were always related to specific stimulus characteristics. For example, participants expected a red circle or a blue circle on a given trial, and were able to prepare a specific response associated with that stimulus. Expectation, in this case, could in principle have served to activate or amplify an existing stimulus-response connection.

However, expectations could also pertain to the more abstract level of task sets. In many experimental paradigms – and in “real life” – the same stimulus can be associated with several different responses, depending on the current task or goal of the actor. For example, a blue circle could be classified according to its size (large/small) or its color shade (bright/dark), each option being associated with a different answer. In task switching paradigms, participants usually have to perform tasks of this kind, either repeating the same task or switching between tasks from trial to trial. If expectation is indispensable for goal-directed action (cf. Kunde et al., 2007), it might also – perhaps especially – be relevant in relation to task sets. Recent results (Duthoo et al., 2012) suggest a prominent role for subjective predictions in task switching. With this study, we wanted to expand upon these findings and examine the role of expectation in task set preparation and cognitive control.

Cognitive conflicts can arise when incompatible response tendencies are activated simultaneously (e.g., Stroop, 1935; Simon, 1969; Eriksen & Eriksen, 1974). Similarily, performance is impaired when people have to switch back and forth between different tasks. Research on task switching has shown that it is notoriously difficult for people to switch from one task set to another, while repeating the same task over and over again usually speeds up responses (see Kiesel et al., 2010, for an overview). Repetition benefits can certainly be explained by associative priming effects, where certain cognitive pathways are strengthened with practice. However, taking into account the importance of subjective expectation for action control, as attested by the first two studies, associative accounts might not give the full picture. If expectation enables preparation for task sets it should in theory be possible to prepare for conflicting tasks as well. As Duthoo et al. (2012) found expectation effects on task switching performance only for repetition trials, this point remains unresolved. In this study we therefore also addressed the question of whether preparation for conflict is possible on the basis of explicit subjective expectation.

To examine the effects of explicit subjective expectation on preparation for task sets, we adapted the paradigm from Studies 1 and 2 for a task switching experiment. Participants had to either identify the size or color shade of a circle, with the task either repeating or alternating between trials. Before the imperative stimulus appeared, participants were asked to predict the *task* (size or color discrimination) or read aloud a word cue indicating the upcoming task. Correctly predicted tasks were carried out faster than false predictions, and faster also than correctly cued tasks. The magnitude of the expectation effect depended upon the validity of predictions: with 80% task alternations (high switch probability), participants were able to score more correct predictions than with 50% task alternations (medium switch probability). The more reliable predictions in turn entailed a larger expectation effect. This is analogous to the finding from Study I, where the size of the cueing effect was contingent on cue validity.

Importantly, and differing from the results of Duthoo et al. (2012), participants in our study were able to adequately prepare for task repetitions *and* alternations. In the high switch probability condition, correctly predicted task alternations were no slower than correctly predicted task repetitions. Overall, there was even a switch benefit in this condition, with task switches being faster than task repetitions. As task alternations were expected more frequently, this finding is in line with an expectation-based account of task preparation. However, as there was a repetition benefit in the medium switch probability condition, it appears reasonable to assume an additional influence of associative priming effects. By employing verbal predictions, we were able to rule out manual priming as a confounding factor (cf. Duthoo et al., 2012).

In conclusion, we found that beyond the preparation of specific stimulus-response connections, explicit subjective expectation enables a more general preparation for tasks. An expected task is carried out faster than an unexpected one. Task performance cannot be reduced to simple associative priming effects, and subjective expectation should be taken into account in research on cognitive control. This contention is underlined by the finding that preparation for cognitive conflict is possible with expectation. An expected task alternation entails no more costs than an expected task repetition, at least when predictions prove to be reliable. Cognitive control, according to this view, is not so much a reactive mechanism contingent upon conflict in previous trials (cf. Botvinick et al., 2001). Instead, it is better conceptualized as a proactive phenomenon, with subjective expectation driving preparation.

As in the first two studies, results in Study III proved self-generated predictions to be more powerful than cue-induced expectations.

4. Discussion

As pointed out above, there is ample evidence to support the view that expectation is a key function of our cognitive system, and that learning and action rely upon it. Measuring expectation, however, remains difficult, as it is subjective by nature and not directly accessible. The agenda of this thesis was to answer three questions crucial to the use of explicit self-generated expectation in experimental paradigms: (1) Are verbalized predictions a valid indicator of internally generated expectations? (2) Do such expectations really affect action preparation? (3) What are the differences between expectations arising from external or internal sources? To answer these questions we conducted three studies as described above.

In all of our studies, participants adapted their predictions to the observed task conditions and relied on them to prepare their responses. We found that verbalized predictions are in fact a valid indicator of subjective expectation and are suitable for use in experimental paradigms. Also, subjective expectation cannot be described as a mere by-product of preparation, but instead feeds into preparation and therefore plays a role in action control. Self-generated expectation was shown to involve early attentional and central decision processes to a greater degree than cue-induced expectation. Consequently, self-generated predictions entailed greater behavioral effects not only for stimulus expectations, but also for expectations regarding a task set. Subjective expectation is therefore also elemental in cognitive control.

While the aim of this work was to show the functional role of explicit expectation in controlling behavior, the cognitive mechanisms by which it influences action control remain subject to speculation. For example, explicit expectations as discussed here could be based upon an “implicit” state of the cognitive system. As stimuli varied in frequency in Study I, the associations between the more frequent stimuli and responses were presumably strengthened and would yield a stronger activation. However, other options might receive some degree of activation too. When generating an explicit expectation from this activation state, the lesser options might be eliminated, amplifying the expectation for just one option in a winner-takes-it-all manner (cf. Kohonen, 1984). This additional mechanism could explain the benefit explicit expectations enjoy over implicit expectations in controlling behavior. While the latter are more or less close to each other on an activation scale, the former are unchallenged by competing options.

As explicit expectations help us to make quick and positive decisions, it is an interesting question what the “normal” expectation mode of our cognitive system is. Research on verbal suppression indicates that explicit verbalizations are performed spontaneously to aid preparation for a task, albeit usually on a subvocal level (e.g., Miyake et al., 2004). If this holds as general principle, explicit expectations might be formed even when not formally required. The findings from our experiments with verbalized explicit expectations could then be extended to situations in which no verbalization takes place. Even when people are not aware of it, they might use this mechanism to clearly set apart one course of action from the many alternatives.

If self-generated expectation assumes a central role in steering behavior, as we argue, what differentiates it from cue-induced expectation (compared in Studies II & III)? One possibility is that there is in fact only one type of expectation, self-generated internally by the cognitive system. If we ask our participants for their predictions, that’s the type that we retrieve, more or less directly. According to this idea, the use of cues is not really suited to induce expectations. Instead, the cues might or might not coincide with the internal expectation state. If the cue matches the internal expectation, it receives a boost similar to a self-generated verbalization. If cue and internal expectation don't match, however, the cue might actually interfere with efficient preparation. As people were not expecting (and preparing for) what the cue indicated, our measures would not show any benefit for the cue in this case. In such a scenario, the use of cues would simply add noise to the measurement and diminish any potential expectation effects. Contrary to the argument that cues allow for a more controlled and accurate manipulation and measurement of expectation, this would mean that in fact self-generated predictions provide a "cleaner" way to assess expectation and are closer to the "true value" of the internal cognitive state. While our results did not allow us to substantiate this account, it might be a worthwhile endeavor to specifically address this question in future research.

The importance of expectation in human cognition and behavior is emphasized in diverse theoretical trends. Proponents of the ideo-motor principle state that expectation is the starting point for all behavior (e.g., Kunde et al., 2007). According to this view, people act to achieve a given goal by matching an experienced outcome to an expected outcome. Returning to the soccer example from the beginning, the anticipation of how she will save the penalty initiates the goalkeeper's dive for the ball. The action is carried out to achieve the desired effect in the environment. Recent research suggests that the acquisition of action-effect associations happens automatically (Gaschler & Nattkemper, 2012), but these effect anticipations are utilized only if participants can freely choose their responses in an intention-based mode of action control (as compared to stimulus-driven responses). In the studies reported here, participants might have acquired action-effect anticipations in both the cueing and the prediction conditions. The effect of these expectations on behavior, however, was fully visible only when participants were required to generate predictions themselves.

In a different vein, researchers into the field of reinforcement learning have long highlighted the role of expectation for incremental adaptation to environmental conditions (e.g., Rescorla & Wagner, 1972). In this framework, learning takes place in the gap between an expected and an actual outcome, the so-called prediction error. If the goalkeeper's prediction proves to be wrong, the experience allows her to learn about the shooter's behavior and generate a more accurate expectation next time. Without a (disconfirmed) expectation, there would be nothing to learn. In implicit sequence learning, researchers have found largely reduced learning when timing constraints (RSI = 0 ms) disabled the opportunity to generate predictions (Martini, Furtner & Sachse, 2013). In the studies reported here, participants were actively required to generate predictions (and to express them vocally). Results from studies in implicit learning and action-effect learning suggest that predictions are spontaneously generated, without explicit requirements and without observable vocal expressions.

Our findings underline the view that expectation is crucial to action preparation. Beyond this broad statement, the results presented here also point to the importance of including self-generated, subjective predictions in research on expectation effects. Outside the lab, reliable cues indicating which action best to perform next are often lacking. Subjective expectation therefore assumes a special role in enabling efficient behavior. An experienced goal-keeper can form more accurate expectations and beat the odds to save the ball.

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Appendix A

Study I

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Does explicit expectation really affect preparation?

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Expectation enables preparation for an upcoming event and supports performance if the anticipated situation occurs, as manifested in behavioral effects (e.g., decreased RT). However, demonstrating coincidence between expectation and preparation is not sufficient for attributing a causal role to the former. The content of explicit expectation may simply reflect the present preparation state. We targeted this issue by experimentally teasing apart demands for preparation and explicit expectations. Expectations often originate from our experience: we expect that events occurring with a high frequency in the past are more likely to occur again. In addition to expectation, other task demands can feed into action preparation. In four experiments, frequency-based expectation was pitted against a selective response deadline. In a three-choice reaction time task, participants responded to stimuli that appeared with varying frequency (60, 30, 10%). Trial-by-trial stimulus expectations were either captured via verbal predictions or induced by visual cues. Predictions as well as response times quickly conformed to the variation in stimulus frequency. After two (of five) experimental blocks we forced participants by selective time pressure to respond faster to a less frequent stimulus. Therefore, participants had to prepare for one stimulus (medium frequency) while often explicitly expecting a different one (high frequency). Response times for the less frequent stimulus decreased immediately, while explicit expectations continued to indicate the (unchanged) presentation frequencies. Explicit expectations were thus not just reflecting preparation. In fact, participants responded faster when the stimulus matched the trial-wise expectations, even when task demands discouraged their use. In conclusion, we argue that explicit expectation feeds into preparatory processes instead of being a mere by-product.

Keywords: explicit expectation, action control, anticipation, preparation, task goals

INTRODUCTION

"You have to expect things of yourself before you can do them," as stated by basketball legend Michael Jordan (http://www.biography.com/people/michael-jordan-9358066). Expectation is elemental in many types of behavior. It allows us to predict and prepare for an upcoming event. It can be implicit, as when we are not aware of it, or explicit. Here we focus on explicit expectations pertaining to an upcoming stimulus. These expectations can be either based on experienced stimulus frequency (made explicit through verbal predictions) or based on cues providing advance information.

Many researchers stress the role of expectation in controlling our behavior (e.g., Kunde et al., 2007; Duthoo et al., 2012). The quote above is just one example of how we take for granted that expectations influence how we go about a task. However, there are prominent findings on action control, which demonstrate that the colloquial notion of expectations influencing preparation needs empirical support. For instance, a recent brain imaging study by Soon et al. (2008) found brain activity reflecting the preparation for a free choice up to 10 s before it entered awareness (mirroring the classic "free will" experiment by Libet et al., 1983). Conscious intention might thus only be an epiphenomenon of preparatory processes in the brain (but see Trevena and Miller, 2010, for opposing evidence). Similarly, when asking someone to verbalize their expectation (about a future event that they will have to respond to) it is unclear whether the verbalized expectation simply *reflects* a preparatory state or whether it can in addition influence task processing. According to the latter view, an explicit expectation (which might be rooted in preparatory processes to some extent) feeds back into task processing. For instance, preparatory processes might be slightly stronger for one vs. another stimulus at the moment an explicit expectation is generated. The explicit expectation might feature just one of the stimuli and preparation for this option might be amplified in a winner-takes-it-all manner, because an explicit expectation had to be generated.

While the notion of expectation as a distinct construct has served as an example for redundant theorizing by critics of early cognitive psychology (e.g., Skinner, 1950) it has gained considerable support through cognitive modeling, where prediction error terms are at the core of many learning models (e.g., Sutton and Barto, 1981), as well as through the discovery of neural correlates (e.g., Schultz et al., 1997). According to Gallistel (2005) expectations have a causal role in human behavior in many economic theories and are the driving force of fast adaptation in animals to changed reinforcement schedules. The concept of expectation is discussed under various labels such as anticipation (e.g., Kunde et al., 2007), expectancy (e.g., Perruchet et al., 2006), and prediction (e.g., Sutton and Barto, 1981). Expectation encompasses both the act of looking forward as well as the thing looked forward to. In the current study, we refer to expectation as the explicit verbal prediction (or descriptive cue) of an upcoming stimulus in a sequential choice task.

In the current study, we wish to put the notion that explicit expectations have a causal role in preparation to the test. As in the work by Soon et al. (2008) we use a broad concept of preparation, encompassing any process, or state of the cognitive system that promotes the (speedy and accurate) execution of a certain action. This can take place anywhere along the cognitive processing chain, from attentional preparation (perception) to response selection (decision) to motor preparation (action). Faster responding has been shown if orientation of attention is possible in advance and facilitates perception (e.g., Posner and Petersen, 1990). On the other hand, processes of response selection and execution also benefit from preparation based on available advance information (e.g., Rosenbaum and Kornblum, 1982), which then results in faster responding. Wherever the facilitation takes place, a prepared action should be executed faster (as measured by RT). Here, we talk about *match effects* when comparing cases in which the required response matches the expectation, vs. cases in which it does not.

Expectations often originate from our experience: we expect that events occurring with a high frequency in the past are more likely to occur again in the future (e.g., Fitts et al., 1963). According to information theory (Shannon, 1948), information gain is low if an event encountered frequently before re-occurs. On the one hand, in this case little can be learned. On the other hand, the occurrence of the expected event usually boosts performance, whereas unexpected events can cause cognitive conflict and impair performance (e.g., Bernstein and Reese, 1965; Posner and Snyder, 1975). In line with the view that explicit expectation can feed back into action preparation, Miller and Anbar (1981) have suggested two routes for the impact of event frequency on action preparation: directly by strengthening S-R associations and indirectly by subjective expectations.

However, in many task situations explicit expectations and other aspects of task preparation favor the same behavior. This renders it difficult to demonstrate that explicit expectation is influencing task processing above and beyond these other aspects. For instance, a frequent S-R connection might be favored both by the high strength of the S-R association as by an explicit expectation, but it is difficult to demonstrate that the latter is actually feeding back into preparatory processes in such a situation. Therefore, we developed a paradigm in which participants can be made to expect one event (by event frequency) while another task demand (severe time constraint on a stimulus which is not the most frequent one) at the same time requires that they are preparing for a different event. If explicit expectations have an effect on task processing in a situation in which one would be better off preparing for a different event than the one expected, this would considerably strengthen the view that explicit expectations are feeding back into preparatory processes. This approach borrows its rationale from Perlman and Tzelgov (2006) who suggested scrutinizing effects that are *not* adaptive. Often, cognitive psychology builds on concepts that lend their credibility to adverse performance effects. If the effect of interest disturbs efficient performance, it is hard to explain it away. In their case, the concept of implicit learning (as distinct from controlled learning processes that in some cases might run in parallel) could be considerably supported by showing that implicit learning takes place even when it hampers performance – more learning led to worse performance. Similarly, our notion of explicit expectation as a distinct source of task processing could be backed by demonstrating dysfunctional performance effects.

In line with our perspective, a recent study by Duthoo et al. (2012) points toward the use of expectation even when it is invalid. We want to extend this finding. If, for example, people expect an event they know is very unlikely to occur, are they still preparing for it? Finding performance gains in such a case (if the unlikely event does occur) would suggest a functional role of expectation (being translated into preparation), despite the largely dysfunctional effects. As a stronger test for the impact of explicit expectation on preparation we introduced a conflicting task demand promoting the preparation of an option different from the one expected. Preparation in terms of "response readiness" (Rosenbaum and Kornblum, 1982) should be susceptible to other influences besides advance information or stimulus expectation. For example, the reinforcement of a certain response should increase its preparation state even if expectation based on past experience or situational cues favors a different response. Significant match effects in this case would suggest an influence of explicit expectation even when it is maladaptive. On the other hand, following the view of conscious intention as epiphenomenon of unconscious determinants of behavior (Libet et al., 1983; Soon et al., 2008), explicit expectations in our study should change in line with changes in preparation. If explicit expectation is merely reflecting rather than influencing task preparation, then explicit expectation should change when task preparation is experimentally changed. There is evidence, however, that subjective expectations can deviate from action preparation based on priming or associative learning (Perruchet et al., 2006). If explicit expectation is assumed to have a function in cognitive processing (as opposed to being a mere by-product) it should not be altered by a task demand that selectively manipulates preparation.

In addition to past experience, expectation can also be based on situational cues. The distinction between these two sources of expectation has been largely overlooked in research on expectation effects (but see Acosta, 1982). Results from our lab (Kemper et al., 2012) point to significant differences: self-generated predictions are accompanied by a distinctive expectation state visible in the contingent negative variation of the electroencephalogram and have a stronger effect on sensoric potentials compared to external cues, resulting in larger behavioral effects. In order to target the role of explicit expectations in preparation on a broad basis, we used both types of explicit expectations in the current study.

MATERIALS AND METHODS

In a series of four experiments, we used a three-choice reaction time task. Stimuli were displayed with different frequencies, with one stimulus being presented in 60% of all trials, another one in 30%, and the last in 10% of all trials. Participants responded to each stimulus by pressing one of three keys. As a measure of trial-wise subjective expectation we asked participants to verbally predict the upcoming stimulus on each trial (Experiment 1: *verbal* *predictions*). To control for effects of this verbalization procedure, we ran a variant where no predictions were required (Experiment 2: *no predictions*). In two additional experiments, we replaced the self-generated predictions with external cues indicating the upcoming stimulus. Cues were either not predictive of the subsequent stimulus presentation (Experiment 3: *non-informative cues*), or they correctly indicated the upcoming stimulus on 80% of all trials (Experiment 4: *informative cues*). In order to test for effects of explicit expectation when it is not perfectly in line with other demands for task preparation, we introduced a response deadline for the medium frequency stimulus toward the second half of all experiments.

EXPERIMENT 1: VERBAL PREDICTIONS

Responses to the more frequent stimuli should generally be faster because of stronger S-R associations and because they are expected more often (Miller and Anbar, 1981). Subjective predictions (in Experiment 1) should also reflect this frequency pattern, with participants more often predicting the more frequent stimuli. A common phenomenon in this context is the tendency of people to match their predictions to the observed probabilities, resulting in fewer correct predictions compared to an optimal strategy (i.e., always predict the most frequent event). This phenomenon has been described as probability matching (e.g., Gaissmaier and Schooler, 2008). Participants should display the same tendency in our task if they really try to predict the upcoming stimulus. Therefore, finding a frequency effect in explicit expectations provides a manipulation check to ensure that participants are in fact correctly performing the task of verbalizing their expectations in our experiment. While actual stimulus presentation was unrelated to these subjective predictions, responses should be faster after (coincidental) correct predictions if people use their predictions to prepare for task execution.

Faster responses to correctly predicted stimuli (match effects) would point toward a mandatory use of subjective expectation in action preparation. Since there is no relation between participants' predictions and the actual stimulus they have to respond to, there is no reliable gain for them in following their predictions. This holds in particular for predictions of the two less frequent stimuli. To challenge the assumption of a mandatory use of explicit expectations even further, we introduced an additional task demand with the goal of diverting preparatory processes away from the response to the expected stimulus. After two of five experimental blocks participants were instructed to give particularly fast responses to occurrences of the medium frequency stimulus (30%). Slow responses on these trials were punished by presenting an unpleasant noise which acted as a negative reinforcement. This additional task demand was therefore at odds with the pattern set up by the stimulus frequencies. While stimulus frequency and subjective expectations should lead to faster responses for the most frequent stimulus, the additional task goal (avoid the unpleasant noise) should lead to a stronger preparation for the medium frequency stimulus. It makes preparation on the basis of frequency expectations less useful because preparing for the predicted response may result in hearing the aversive sound in some cases (i.e., when the frequent stimulus is predicted and prepared and the medium frequent stimulus occurs and is responded to too slowly). Still finding match effects under these conditions would be further evidence for the mandatory use of explicit expectation in preparing for an upcoming task. To the extent participants are able to adjust their preparation to the requirements of the actual task one could expect reduced expectation match effects in blocks three to five: participants should rely less on their stimulus predictions if the medium frequent response is reinforced.

Match effects (faster responses following correct predictions) are in line with our idea that people use their explicit subjective expectations in action preparation. However, there is the possibility that these expectations are simply a by-product of preparation without functional use. In this case, participants should adjust their predictions in line with the changes in action preparation once the additional task demand is established. If participants in fact prepare to respond to the medium frequency stimulus, and if their stimulus expectations are inseparably linked to this preparation (as in "reading out" an internal preparation state determined by the strength of specific S-R associations), this should be reflected in their prediction frequencies. In this case, match effects might not be reduced (see above), as both preparation and prediction would follow the altered task demands. If, on the other hand, people generate expectations independently of action preparation that is fueled by a second task demand, the frequency pattern should remain intact in their subjective predictions.

EXPERIMENT 2: NO PREDICTIONS

In Experiment 1 verbal predictions were required before each stimulus occurrence resulting in a dual-task like situation: to generate verbal predictions and to perform the manual choice reaction task. This could have resulted in different processing of the choice task as compared to solely producing choice reactions. In order to verify the results found for frequency and, particularly, the effect of selective reinforcement of the medium frequent stimulus, we repeated the experiment without verbal predictions.

EXPERIMENT 3: NON-INFORMATIVE CUES

Expectation effects are most often investigated by using external advance information (provided by cues, e.g., Posner and Snyder, 1975; Miller and Anbar, 1981; Mattler, 2004). It has been shown, however, that expectations induced by cues affect performance differently from predictions generated by participants themselves (Kemper et al., 2012). Against this background we repeated Experiment 1 and replaced verbal predictions with visual, non-verbal cues that announced one of the three stimuli in advance before the imperative stimulus was presented. The probability of match was kept at approximately the same level as in the prediction experiment by presenting the cues with the same frequencies as the stimuli (10, 30, and 60%) but randomized independently of stimulus presentation. The general effect of stimulus frequency should be similar to the previous experiments, as well as the impact of the selective response deadline. In line with previous studies (Acosta, 1982; Kemper et al., 2012) we expect a smaller match effect with cues than with predictions.

EXPERIMENT 4: INFORMATIVE CUES

We conducted Experiment 4 for two reasons. First, the use of non-informative cues is quite atypical for investigating expectation effects by the help of external advance information. Usually, cueing effects on preparation appear only with highly reliable cues (e.g., Alpay et al., 2009; Scheibe et al., 2009). The reason for finding an effect under such unfavorable conditions as in Experiment 3 might lie in feature overlap between cue and stimulus. Second, we wanted to explore an idea that could explain the difference in effectiveness between explicit expectations generated by the individual or provided by external advance information. As the overall real validity of predictions (Experiment 1) and cues (Experiment 3) was comparable the difference might in fact go back to the degree to which participants rely on their expectation, depending on its source. One possible mechanism could be that participants weight self-generated predictions stronger and that external information has to be of a much higher validity to be included into controlled action preparation, or, alternatively, predictions and cues differ in subjective usefulness.

Therefore, in Experiment 4 we increased the probability of match between cue and stimulus feature to 80%. Under these conditions a much larger effect of expectation match than in Experiment 3 should be observable. We expect comparable effects of stimulus frequency as in the previous experiments, as well as an effect of selectively reinforcing the medium frequent stimulus by use of a deadline.

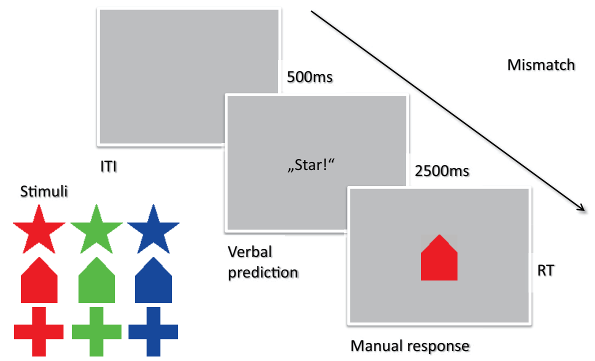

FIGURE 1 | Task used in Experiment 1. On each trial, participants had to verbalize their prediction for the upcoming stimulus (in this case "star"). After 2500 ms the stimulus appeared on screen (in this case a house, signifying a mismatch) and participants had manually respond by pressing one of three keys. The next trial started 500 ms after the response. For any given participant, only one of the two stimulus features (shape, color) was relevant throughout the task (in this case, both predictions and responses pertained to the shape of a stimulus).

Participants

One hundred five undergraduate students of psychology and other fields (74 women, mean age = 24.9 years) participated in individual sessions lasting approximately 90 min (Experiments 1 and 2) or 60 min (Experiments 3 and 4). Participants either received partial course credit or were paid 8–12 euros for their time. They provided written informed consent, particularly to the exposure to aversive sounds.

Design and procedure

In all of the experiments reported here, we used a three-choice reaction time task. Three different shapes served as stimuli – star, house, and cross – that were presented in one of three colors, red, green, or blue. Each stimulus could be named by a monosyllabic word in order to provide for approximately equal verbalization times (for Experiment 1; German "Stern," "Haus," "Kreuz," or "rot," "grün," "blau"). Stimuli were displayed centrally on a 17″ CRT computer monitor with a light gray background and occupied approximately 2.2 cm in width and height (corresponding to a visual angle of about 6.4° at a viewing distance of 60 cm). Three keys (V, B, and N) on a standard Windows keyboard were mapped by instruction either to the three shapes or the three colors, with the relevant feature varying between participants. The task and stimuli are shown in **Figure 1**.

Frequency of the three possible shapes or colors, respectively, was predetermined in the stimulus set to yield three frequency classes, frequent (60%), medium (30%), and infrequent (10%) for the relevant stimulus feature. Occurrence of the irrelevant feature was equally distributed and co-occurrence was balanced across features. Half of the participants used shapes as relevant feature for predictions and response selection and the others used color. The irrelevant feature was not used in this task.

Participants completed five blocks of 120 trials for a total of 600 trials. The frequent stimulus occurred in 72 trials, the medium frequent in 32 trials, and the infrequent stimulus in 12 trials per block. After the first two experimental blocks the additional task demand was introduced. Participants were informed that their reactions to the medium frequency stimulus (which was simply described by its label) had to be extra fast if they wanted to avoid the annoying sound on their headphones. This aversive auditory stimulus, a white noise burst of about 75 dB, had been demonstrated to participants at the beginning of the session before they gave their consent to the procedure. The response deadline for the medium frequency stimulus was individually determined at the median reaction time for the frequent stimulus in the preceding Block 2 and kept constant over the remaining three blocks. If participants exceeded this deadline on any given trial with the medium frequency stimulus, the aversive sound was immediately presented on their headphones and ended 500 ms after their (late) reaction.

At the end of the session participants were asked to estimate the frequency of the relevant stimulus feature.

EXPERIMENT 1: VERBAL PREDICTIONS

On every trial, participants were asked for their subjective expectation regarding the upcoming stimulus. According to the relevant stimulus feature, the prompt "Farbe?" or "Form?" (German for color or shape) were displayed on the screen. Participants then had 2500 ms to verbalize their expectation. If voice onset was registered more than 1500 ms after the onset of the prompt, participants were reminded to speak as soon as the prompt is shown on the next trial. In addition, participants were randomly reminded in 10% of all trials to speak loudly and clearly. After this expectation interval (2500 ms after the prompt onset) the stimulus was shown and participants had to press the corresponding key on the keyboard. The following trial started 500 ms after the response. The experimental blocks were preceded by three practice blocks of 18 trials each in which manual responses and verbal expectations were first trained separately and then combined. Frequency and combinations of relevant and irrelevant stimulus feature were equally distributed in the practice blocks.

Verbal expectations were captured with a microphone headset and identified using a real-time speech recognition program implemented in Matlab (Donkin et al., 2009). At the beginning of the experimental session, the software was trained to the individual voice with the participant repeating the words in the response set 10 times. This was followed immediately by an accuracy check with 10 additional exemplars per word. If recognition accuracy was below 95% (i.e., more than one misidentification) the original training was restarted, otherwise the additional exemplars were added to the pool of training exemplars and the experiment commenced. Recognition accuracy was tested again at the end of the session.

EXPERIMENT 2: NO PREDICTIONS

The task was the same as in Experiment 1, with the only difference that participants were not instructed to generate verbal predictions at the beginning of each trial. Instead of the prompts used in Experiment 1 a fixation dot was displayed for 2500 ms to keep the timing equivalent to Experiment 1.

EXPERIMENT 3: NON-INFORMATIVE CUES

Again, the task was largely the same as in Experiment 1. Instead of prompting participants to verbalize their subjective expectations on each trial symbolic cues were presented predicting the upcoming stimulus. These cues were similar to the imperative stimuli but only varied in the relevant feature: if a participant had to respond to the shape of a (colored) stimulus the cues consisted of black shapes, if color was the relevant feature colored circles were used as cues. Participants did not have to verbalize the cues. Cues were displayed 1000 ms after the last response and remained visible for 1000 ms followed by a blank screen for another 1000 ms, after which the imperative stimulus appeared. Thus, the response-stimulus interval was the same as in the other experiments (3000 ms) and the timing of the cues was similar to the verbal predictions in Experiment 1. Importantly, cue presentation was randomized independently and was not related to the subsequent stimulus presentation. Therefore cues exhibited the same low overall validity as the predictions in Experiment 1: on only 46% of all trials was a cue followed by the corresponding stimulus (60% for the frequent stimulus, 30% for the medium, and 10% for the infrequent stimulus).

EXPERIMENT 4: INFORMATIVE CUES

The task was the same as in Experiment 3, except that the validity of cues was 80% for all frequencies. Thus, in 80% of all trials a cue was followed by the corresponding stimulus.

RESULTS

EXPERIMENT 1: VERBAL PREDICTIONS

Three participants were excluded for producing too many false responses (>10%), another two participants were excluded because of problems with the speech recognition software (<75% accuracy in the post-experiment test). Data of the remaining 19 participants were analyzed. For the following analyses all trials were recruited, including those with immediate stimulus repetitions. The proportion of stimulus repetitions naturally were related to stimulus frequency, with 60% repetition trials for the frequent stimulus, and 29 and 9% respectively for the medium and infrequent stimuli. All results reported here remain unaltered if stimulus repetitions, i.e., 46% of all trials, are excluded. RT analyses are based on correct responses only, excluding error trials. The response deadline, representing the median reaction time for the frequent stimulus in Block 2, was on average set at 424 ms (SD = 76 ms), with individual participants ranging between 303 and 633 ms. In 28% of the trials with the reinforced stimulus, participants passed this deadline and were consequently exposed to the aversive sound (32% in Block 3, 24% in Block 4, 27% in Block 5).

Our experiments, except Experiment 2 with no predictions, included three within-subjects factors: *match* (testing the effectiveness of explicit expectation), *block* (mirroring the effect of training and, more importantly, of the introduction of the response deadline from block 2 to block 3), and *frequency*. A three-factorial repeated measures ANOVA could not be run as participants did not contribute enough data points to one of the cells (match trials for the infrequent stimulus occurred too rarely to get reliable medians per block). Therefore, three two-way ANOVAs were run over the response times and error rates of all experiments: one with *frequency* and *block* to examine the general effect of selectively reinforcing the medium frequent response, one with *match* and *frequency* to look for a potential dependency of the size of expectation effects on experienced stimulus frequency, and one with *match* and *block* to examine the interaction of expectation and the deadline manipulation. In the context of a Bonferroni correction we divided the critical significance level (alpha = 0.05) by three in order to account for repeated tests on one and the same data set.

Before the introduction of the response deadline, RTs and errors followed stimulus frequency. The infrequent stimulus led to the slowest and most error prone reactions and the responses to frequent stimuli were the fastest and most accurate. The medium frequency stimuli lay in between. With the response deadline, in the last three blocks, responses to the medium frequency (reinforced) stimulus became faster than responses to the more frequent stimulus, while response times for all stimuli decreased. A two-way repeated measures ANOVA with the factors *frequency* and *block* revealed main effects for both *frequency*, $F(2, 36) = 81.63$, $p < 0.001$, and *block*, $F(4, 72) = 82.27$, $p < 0.001$, as well as an interaction, $F(8, 144) = 15.91$, $p < 0.001$. Importantly, the selective speedup of responses to the medium frequent stimulus was not achieved at the expense of a higher error rate for the frequent stimulus (see **Figure 2**, top left). The same effects as in RT were found in the error rates (all $p < 0.001$).

Verbal predictions already reflected the frequency differences in the first block and approached the actual values over the course of the experiment. Importantly, this pattern was not altered with the introduction of the response deadline in the third block (see **Figure 3**). Therefore, participants continued to expect the most frequent stimulus most often but reacted fastest to the medium frequency stimulus. The three different stimuli were predicted in the order of their frequency of occurrence (most often the most frequent stimulus, less often the medium frequent stimulus,

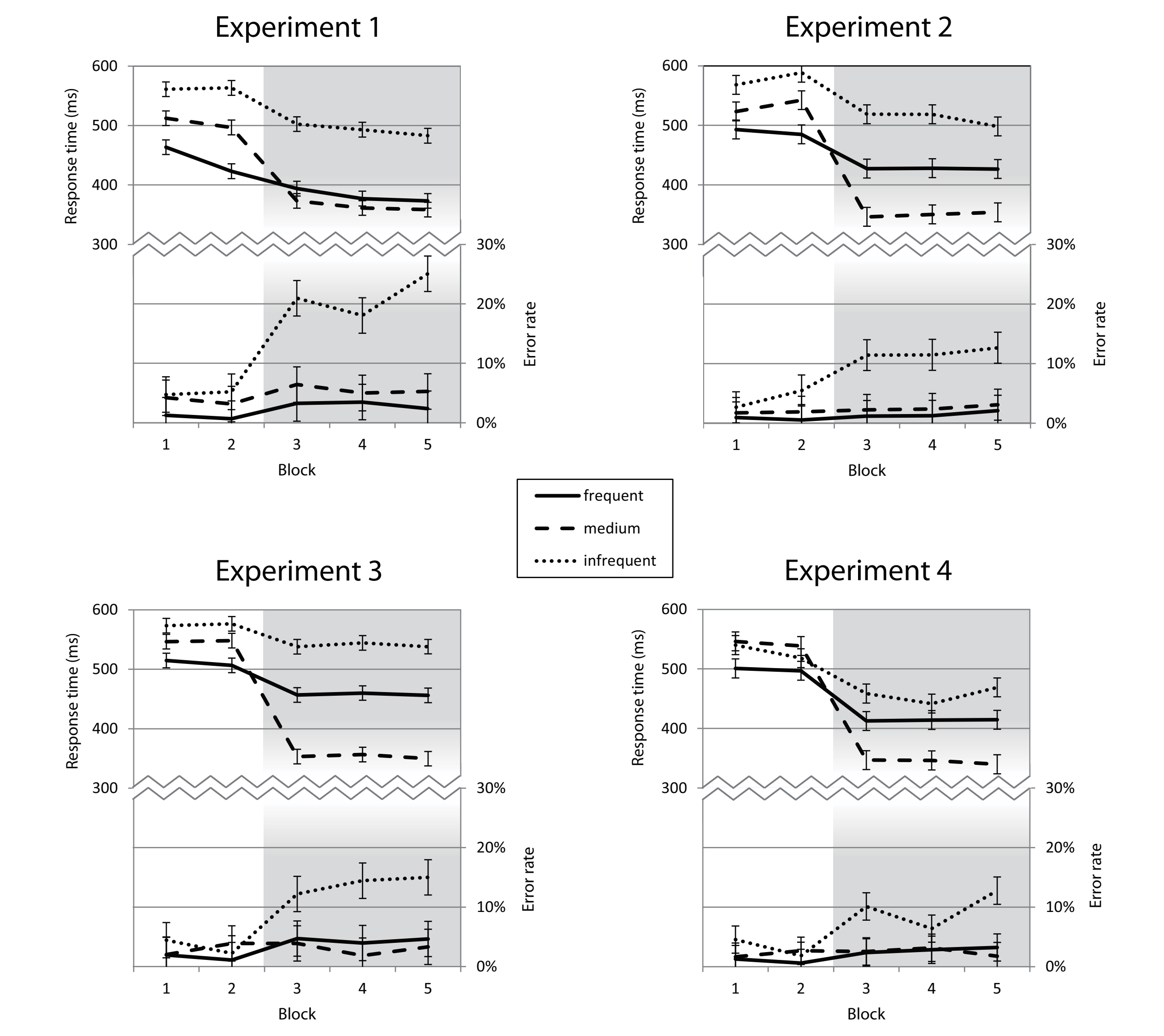

FIGURE 2 | Response times and error rates for Experiments 1–4. Response times (on the top of each panel) exhibit an effect of stimulus frequency (with the frequent stimulus, marked by the solid line, leading to faster responses than the medium and infrequent stimuli) in the first two blocks, as well as an effect of the additional task goal starting in the third block (with the reinforced medium stimulus getting faster responses). The same pattern is visible in conditions with verbal predictions (Experiment 1) and without (Experiment 2) and also with low and high validity non-verbal cues (Experiments 3 and 4).

and least often the rare stimulus). This rank order of prediction frequencies stayed the same over the experiment, so that prediction behavior was highly correlated over blocks (correlation of ranks between successive blocks: $\tau = 0.74$, 0.79, 0.92, and 0.83, all $p < 0.001$), regardless of the changed pattern in choice performance.

Stimuli matched predictions in 42% of all trials (with a minimum of 40% in Block 1 and a maximum of 44% in Block 4; 51% matches for the frequent stimulus, 30% for the medium, and 18% for the infrequent stimulus). Response times were shorter for trials in which the stimulus matched the participant's prediction, as compared to mismatch trials. This match effect was visible for all stimulus frequencies. The ANOVA with the factors *match* and *frequency* revealed main effects on RT for *match*, $F(1, 18) = 130.72$, $p < 0.001$, and *frequency*, $F(2, 36) = 74.55$, $p < 0.001$, but no interaction *match* × *frequency*, $F(2, 36) = 2.77$, ns. After introducing the response deadline for the medium stimulus, the mean difference between match and mismatch trials declined from 110 ms in Block 2 to 60 ms in Block 3 (see **Figures 4** and **5**, top left).The ANOVA with the factors *match* and *block* revealed main effects on RT for *match*, $F(1, 18) = 107.63$, $p < 0.001$, and *block*, $F(4, 72) = 81.14$, $p < 0.001$, as well as an interaction *match* × *block*, $F(4, 72) = 30.56$, $p < 0.001$. The same effects were found in the error rates (all $p < 0.001$).

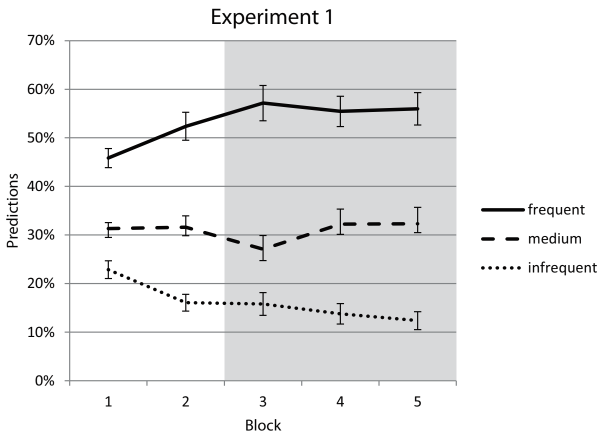

FIGURE 3 | Predictions in Experiment 1 already reflect the varying stimulus frequencies in the first block and approach the actual values (60, 30, and 10%) over the course of the experiment. The additional task goal introduced in the third block does not change this pattern.

The *post hoc* estimates of stimulus occurrence in percent made by the participants also provided a good approximation of the actual frequencies, with the frequent stimulus at 63%, the medium at 24%, and the infrequent stimulus at 13%.

EXPERIMENT 2: NO PREDICTIONS

One participant was excluded from analyses for producing too many false responses (>10%). Data of the remaining 21 participants were analyzed. The response deadline was on average fixed to 491 ms (SD = 89 ms), with individual participants ranging between 333 and 693 ms. On 8% of the trials with the reinforced stimulus, participants exceeded this deadline and were consequently exposed to the aversive sound (9% in Block 3, 7% in Block 4, 9% in Block 5).

The same pattern emerged as in Experiment 1: Responses were faster and more accurate to the more frequent stimuli in the first two experimental blocks, before the introduction of the response deadline. With the deadline, in the last three blocks, responses to the reinforced medium frequent stimulus became faster than responses to the frequent stimulus, while response times for all stimuli decreased (see **Figure 2**, top right). A two-way repeated measures ANOVA on RTs with the factors *frequency* and *block* revealed main effects of both stimulus *frequency*, $F(2, 40) = 71.87$, $p < 0.001$, and *block*, $F(4, 80) = 58.96$, $p < 0.001$, as well as an interaction, $F(8, 160) = 25.02$, $p < 0.001$. The same effects were found in the error rates (all $p < 0.001$).

The *post hoc* estimates again provided a good approximation of the actual frequencies, with the frequent stimulus at 64%, the medium at 25%, and the infrequent stimulus at 11%.

EXPERIMENT 3: NON-INFORMATIVE CUES

Seven participants were excluded from analyses for producing too many false responses (>10%). Data of the remaining 30 participants were analyzed. The response deadline was on average fixed at 502 ms (SD = 75 ms), with individual participants ranging between 383 and 695 ms. On 8% of the trials with the reinforced stimulus participants exceeded this deadline and were consequently exposed to the aversive sound (9% in Block 3, 7% in Block 4 and 5).

Similar to Experiment 2, RTs followed stimulus frequency in Blocks 1 and 2, but the medium frequency stimulus elicited the fastest responses when the reinforcement procedure started after Block 2 (compare **Figure 2**, bottom left). A two-way repeated measures ANOVA with *frequency* and *block* revealed main effects on RT for *frequency*, $F(2, 58) = 107.33$, $p < 0.001$, and *block*, $F(4, 116) = 71.45$, $p < 0.001$, as well as an interaction *frequency* × *block*, $F(8, 232) = 61.28$, $p < 0.001$. The same effects were found in the error rates (all $p < 0.001$). The RT effect of cue match was clearly present for all frequencies as well, but smaller than the effect of expectation match in Experiment 1. The ANOVA with *match* and *frequency* revealed main effects on RT for *match*, $F(1, 29) = 21.57$, $p < 0.001$, and *frequency*, $F(2, 58) = 80.11$, $p < 0.001$, but no interaction *match* × *frequency*, $F(2, 58) = 0.43$, ns. In the error rates, only frequency yielded a significant effect, $F(2, 58) = 16.64$, $p < 0.001$. After the introduction of the response deadline the match effect was diminished from 35 ms in Block 2 to 19 ms in Block 3 (see **Figures 4** and **5**, bottom left). The third ANOVA with *match* and *block* revealed main effects on RT for *match*, $F(1, 29) = 23.41$, $p < 0.001$, and *block*, $F(4, 116) = 44.47$, $p < 0.001$, as well as an interaction *match* × *block*, $F(4, 116) = 13.74$, $p < 0.001$. The same effects were found in the error rates (all $p < 0.01$).

The *post hoc* estimates again provided a good approximation of the actual frequencies, with the frequent stimulus at 57%, the medium at 30%, and the infrequent stimulus at 13%.

EXPERIMENT 4: INFORMATIVE CUES

Four participants were excluded from analyses for producing too many false responses (>10%). Data of the remaining 18 participants were analyzed. The response deadline was on average fixed to 497 ms (SD = 120 ms), with individual participants ranging between 311 and 708 ms. On 11% of the trials with the reinforced stimulus participants passed this deadline and were consequently exposed to the aversive sound (13% in Block 3, 12% in Block 4, and 9% in Block 5).

As shown in **Figure 2** (bottom right), RTs followed stimulus frequency in the first two blocks until the onset of the reinforcement of the medium frequency stimulus at the beginning of Block 3 led to faster responses to this stimulus. The two-way repeated measures ANOVA with *frequency* and *block* revealed main effects on RT for *frequency*, $F(2, 34) = 45.83$, $p < 0.001$, and *block*, $F(4, 68) = 34.74$, $p < 0.001$, as well as an interaction *frequency* × *block*, $F(8, 136) = 22.99$, $p < 0.001$. The same effects were found in the error rates (all $p < 0.001$). RT effects of match between cue and stimulus were much more pronounced than in the low validity variant explored in the previous experiment and were not reduced after the introduction of the response deadline (102 ms in Block 2, 98 ms in Block 3, see **Figures 4** and **5**, bottom right). Accordingly, the ANOVA with *match* and *block* revealed main effects on RT for *match*, $F(1, 17) = 110.14$, $p < 0.001$, and *block*, $F(4, 68) = 41.30$, $p < 0.001$, but no interaction *match* × *block*, $F(4, 68) = 0.55$, ns. The third ANOVA with *match* and *frequency* revealed main effects on RT for *match*, $F(1, 17) = 113.20$, $p < 0.001$, and *frequency*, $F(2,$

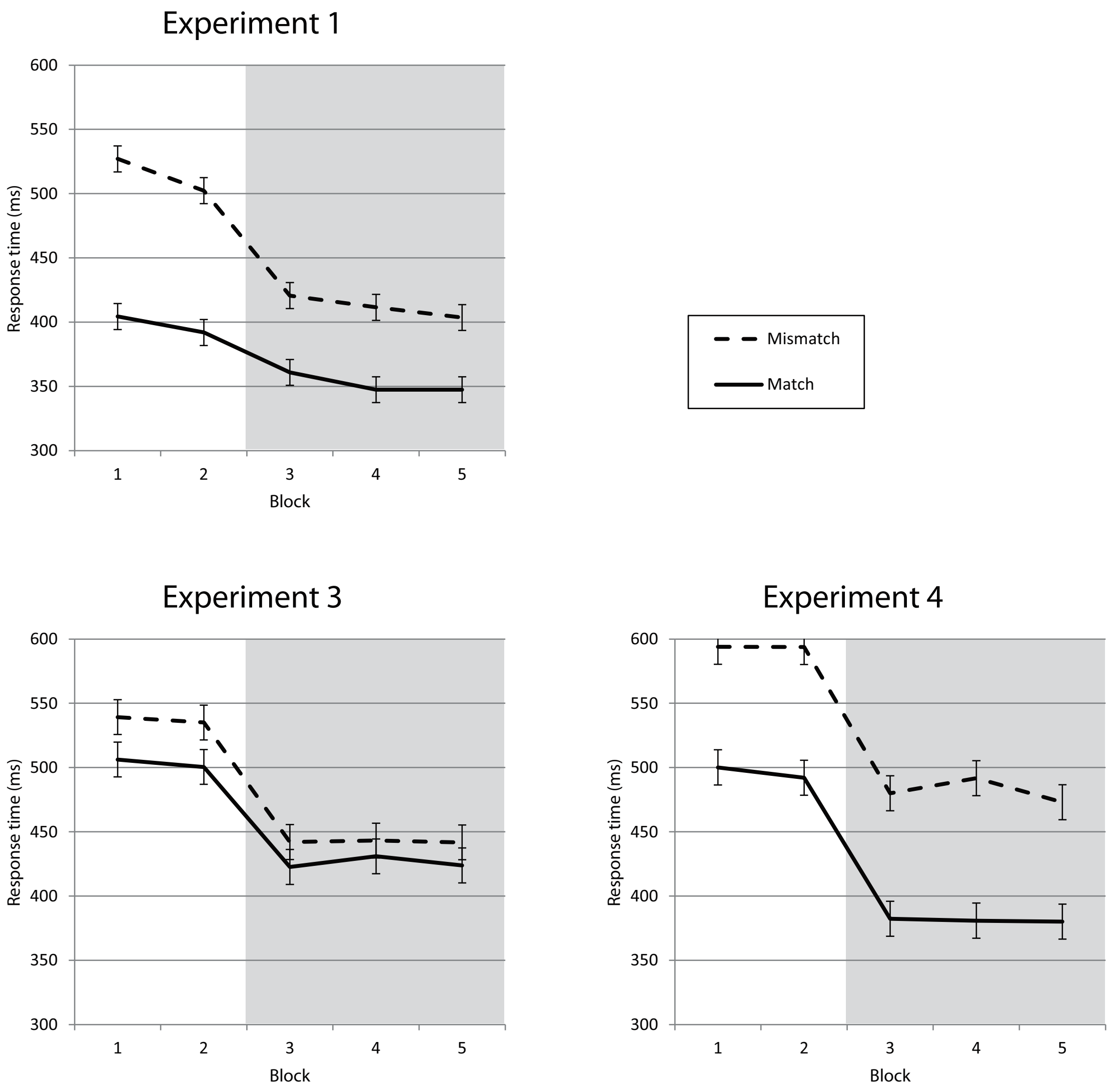

FIGURE 4 | Match vs. mismatch trials for Experiments 1, 3, and 4 (pooled over frequencies). Responses following correct predictions (match) in Experiment 1 are 117 ms faster on average compared to incorrect predictions (mismatch) in the first two blocks; after the introduction of the selective response deadline for the medium frequency stimulus this difference is reduced to 60 ms on average. In Experiment 3, using invalid cues (similar to the predictions of Experiment 1), the difference between match and mismatch trials averages 34 ms at the beginning and is down to 17 ms with the additional task demand. Experiment 4 shows no reduction in this mismatch effect, with 98 ms before and 100 ms after the introduction of the deadline on average.

34) = 76.56, $p < 0.001$, but no interaction *match × frequency*, F(2, 34) = 7.56, ns.

The *post hoc* estimates again provided a good approximation of the actual frequencies, with the frequent stimulus at 56%, the medium at 30%, and the infrequent stimulus at 14%.

DISCUSSION

In all four experiments reported here, stimulus frequencies (60, 30, 10%) were reflected in response times and error rates, with the most frequent stimulus producing the fastest and most accurate responses. While discussion about the role of conscious intention in controlling behavior (Libet et al., 1983; Soon et al., 2008; Trevena and Miller, 2010; see Introduction) might be taken to suggest that explicit expectations merely reflect other preparatory processes but do not influence them, our results suggest that explicit expectations feed back into task processing and thus have a causal role. We disentangled explicit expectation from other forms of preparation by adding a secondary task demand. With instruction and a response deadline combined with an aversive sound, participants were encouraged to prepare for a different stimulus (i.e., the medium frequency stimulus) than the one they were expecting most often (i.e., the high frequency stimulus). Explicit

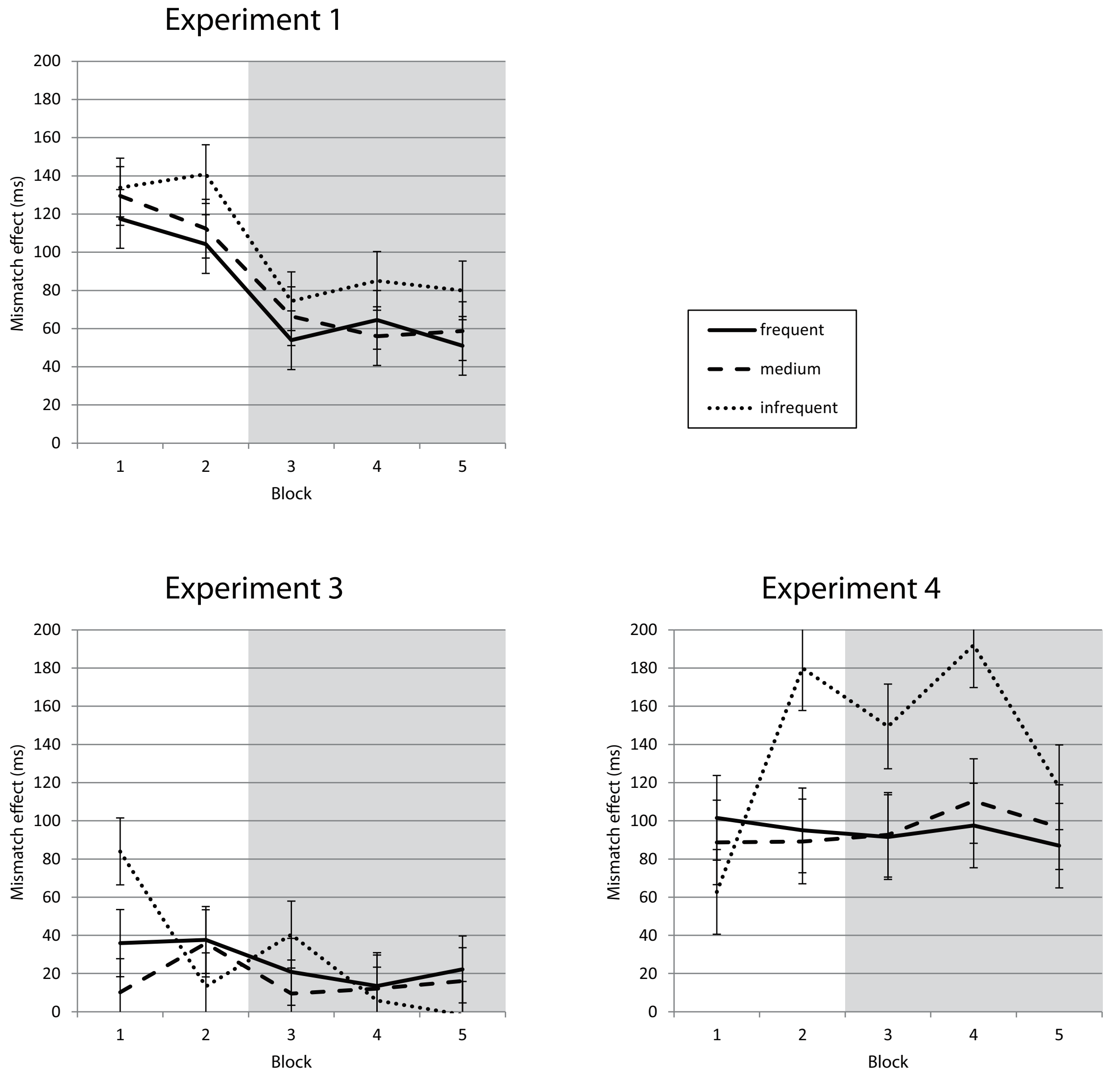

FIGURE 5 | Mismatch effect for Experiments 1, 3, and 4 (displayed by frequency). No differences in mismatch effect between frequencies, similar reduction (Experiment 1) or stability (Experiment 3) with the additional task goal introduced in Block 3. Values from infrequent stimuli are statistically unreliable because of the low number of match trials.

expectations affected task processing even when it would have been beneficial not to rely on them: On the one hand, effects of expectation conflicted with the requirement to respond faster than the response deadline on the medium frequency stimulus. This could have largely been avoided if participants had either not have turned verbalized expectation into task preparation or, alternatively, would have started to explicitly expect the medium frequency stimulus in most or all trials. On the other hand, participants showed faster response times when their expectation matched rather than mismatched the stimulus even in case of the infrequent stimulus – which they sometimes expected. Such an expectation was mostly followed by the frequent or medium frequent rather than the infrequent stimulus. In principle one could have betted on and prepared for the frequent or medium stimulus, despite verbalizing an expectation for the infrequent one. A mismatch was much more likely than a match after such a prediction, yet matches were faster than mismatches. It would have been conceivable that participants show RT benefits of expectations matching the stimuli in case of frequent and medium frequency stimuli and a reversal of the expectation match effect in case of the infrequent (10%) stimuli. For instance, Notebaert et al. (2009) have reported that in cases with a majority of error trials RTs are prolonged after the rare correct trials rather than after error trials, suggesting that event frequency rather than match vs. mismatch of task demands and action can drive performance costs. This does not seem to count for explicit expectations, however.

Thus, neither were explicit expectations themselves chosen flexibly to boost performance, nor could the aftereffects of these expectations be flexibly regulated. The results thus suggest that explicit expectations influence rather than merely reflect other preparatory processes and do so rather inflexibly. Explicit expectations seem to count – even when they are not adaptive to current task demands.

In the current experiments we took two different approaches by measuring expectations through verbal predictions and inducing them by cues. In *Experiment 1* we asked participants to verbally predict the upcoming stimulus on each trial and then respond to the actual stimulus by pressing the corresponding key. Verbal predictions (as a measure of subjective expectation) mirrored actual stimulus frequencies already in the first experimental block, with participants predicting the most frequent stimulus on a higher proportion of trials. When the imperative stimulus matched the prediction on a given trial, participants responded much faster compared to trials on which the stimulus violated their prediction. This gain was similar for all three stimulus frequencies, suggesting that participants used their predictions to prepare the response even if it was unlikely to be fulfilled (18% for the infrequent stimulus, compared to 51% for the frequent stimulus). Introducing the response deadline for the medium frequency stimulus reduced this match effect from 117 to 60 ms, while predictions themselves were not altered.

In *Experiment 2* we replicated the effects of stimulus frequency without verbal predictions, ruling out the possibility that the response time effects found in Experiment 1 were dependent on the second task of explicitly verbalizing stimulus expectations. In *Experiment 3* we induced explicit expectations through symbolic cues. As cue presentation was not related to the subsequent stimulus, their predictive value was as low as that of the self-generated predictions in Experiment 1. There was a small match effect with faster responses following correct cues (34 ms) before the introduction of the response deadline that was diminished to a statistically non-significant difference (17 ms) with the additional task demand. In *Experiment 4*, with cues correctly predicting the upcoming stimulus in 80% of all trials, there was a large match effect that was not reduced by the response deadline (98 ms before, 100 ms after the manipulation). This deviates from the patterns found in Experiments 1 and 3, where the additional task demand (fast responses on the medium frequency stimulus to avoid the aversive tone) led to a reduction in the match effect.

DOUBLE IMPACT OF STIMULUS FREQUENCY

In addition to explicit expectations, RT was affected by stimulus frequency in all four experiments. This is in line with earlier calls to integrate associative as well as an expectancy-based accounts of action preparation. For instance, Miller and Anbar (1981) argue that frequency effects on response time can arise directly (through the strength of S-R associations) and indirectly (through subjective expectancies). Asking participants to verbalize their expectations (in Experiment 1) might have led to larger RT differences between stimuli of different frequency compared to the variants without predictions (Experiment 2) or with external cues (Experiments 3 and 4). Frequency effects might have been prominent on two rather than just one path in Experiment 1. As frequency effects remained evident after the introduction of the response deadline for the medium frequency stimulus, this is pointing toward an automatic effect of S-R frequency and as such toward an independent contribution of this source.

Subjective expectations measured as predictions in Experiment 1 closely mirrored the frequency pattern, a phenomenon also known as probability matching (e.g., Gaissmaier and Schooler, 2008, see below). Thus, performance in predicting the upcoming stimulus was also influenced by the given frequency pattern. The participants presumably made use of their prior experience represented in associations of varying strength. However, the *effect* of subjective expectation and the general effect of frequency on performance in the choice task appear to be independent from each other. Match effects were of similar size for all frequencies, or, to put it differently: the general effect of frequency proved to be the same, regardless of expectation match. This also holds for the experiments where cues instead of predictions were used. That is, the influence of explicit expectation on task processing appears to be different from other effects that arise from stimulus frequencies.

PREDICTIONS: MATCHING VS. MAXIMIZING

Predictions were generated and used in a less than optimal manner. Participants could have maximized their correct predictions (in Experiment 1) by always predicting the most frequent stimulus (which would have lead to 60% matches). Instead, they apparently tried to reproduce the observed stimulus frequencies in their predictions (resulting in only 42% matches). This behavior is in line with the probability matching phenomenon (e.g., Gaissmaier and Schooler, 2008). Trials with expectations matching the stimulus were faster than those with a mismatch. For boosting performance in the choice reaction task it would have been favorable to choose to predict the most frequent stimulus on all trials in the first part of the experiment and the medium frequency stimulus once the response deadline on this stimulus was set in place. Maximizing has been observed in the literature on strategy change in skill acquisition (e.g., Touron and Hertzog, 2004; Gaschler and Frensch, 2007, 2009) where people tend to exclusively choose the one of two processing strategies that is the most suitable on most of the trials. This however, might be an exception as in many other task contexts probability matching has proven to be a robust phenomenon (see, e.g., Gallistel, 2005, for a discussion). He suggested that probability matching is a "hard-wired" policy which is useful in dynamic environments as it guarantees continuous sampling of the options so that an agent does not run the risk of missing to notice changes in which options are currently more or less rewarding. Our results lend further support to this "hard-wired" view, as the *influence* of the probability-matched expectations appears not to be easily adapted to more promising strategies either. However, we do not know for certain what the goals of our participants in optimizing their task performance are. It is possible that they tried to find a balance between the two tasks of realistically predicting stimuli while performing rapidly and correctly on the choice task. Therefore, instructing them to increase their proportion of matches might change the pattern of results.

CONFLICTING TASK DEMAND ATTENUATES IMPACT OF EXPECTATION

The match effects we found, with faster responses following correct predictions and valid cues, are compatible with the idea that explicit expectation serves as a trigger for action preparation and thus assumes a causal role in cognitive processing. However, there are differences in the robustness of these match effects that depend on the source of expectation on the one hand and on its validity on the other hand.

The additional task demand of trying to respond quickly to the medium frequency stimulus in order to avoid hearing the unpleasant sound significantly reduced the match effects in Experiments 1 and 3, but not in Experiment 4. While in Experiment 4 the cue was highly predictive of the stimulus, explicit expectations (Experiment 1) and cues in Experiment 3 were equally unreliable. Arguably, the strong associations between cue and stimulus in Experiment 4 were still fully effective under the response deadline, whereas the impact of the unreliable predictions in the other experiments could be attenuated. Importantly, the match effect was reduced for all stimuli to a similar extent. The predictions that could have boosted the processing of the medium frequency stimulus with the deadline attached to it, were apparently not spared. Rather, participants seem to have relied somewhat less on expectations in general.

While the influence of the non-informative cues (in Experiment 3) on response time was effectively removed by the additional task demand, subjective predictions retained a significant impact. This suggests that self-generated predictions are mandatorily processed and trigger action preparation even if they are obviously unreliable and if task demands favor the preparation of a different action. As Kunde et al. (2007) argue, expectation is an integral component of action control. Expectations are always generated and translated into preparation (of perception or action) as this is usually beneficial to optimize behavior in real life. Artificial external cues do not share this processing privilege by default and have to first prove their usefulness (reliability). When they do, however, as in Experiment 4 (with 80% valid cues), they retain their influence in spite of the additional task demand.

EXPECT ONE THING, PREPARE FOR ANOTHER

The selective reinforcement of the medium frequent stimulus led to a selective speed up of responses to the reinforced stimulus. Thus, participants in our study apparently were able to predict one thing while at least partly preparing for another. A similar dissociation between explicit expectation and overt behavior has been reported before (Perruchet et al., 2006) for simple reactions in an associative learning experiment. In the "Perruchet effect," response time (as a measure of automatic activation) decreases with increasing number of repeated associations, while explicit expectation develops in the opposite direction, increasingly favoring an alternation after longer runs of repetitions (the "gambler's fallacy"). However, in contrast to the build-up of associative effects, in our study the change in performance occurred immediately after instructing the new requirement, rather than gradually. The abrupt effect of the deadline suggests that intentional control processes can influence the extent to which learned S-R connections impact behavior. The ordering of RTs by stimulus frequency was immediately altered. With the stimulus-specific deadline, the RT for the medium frequency stimulus surpassed RT for the frequent stimulus. In line with the intentional weighting principle proposed by Hommel et al. (2001), intentional control might put some extra strength on a response alternative that would have been otherwise weak and so alter the result of the competition for response selection. Put differently, if something we have learned earlier (as, e.g., expecting stimuli with a given frequency) conflicts with actual task goals (as, e.g., responding fast to a less expected stimulus), behavior will always be the result of resolving this – classical – conflict situation (see Botvinick et al., 2001). If expectations conflict with other task demands it seems feasible to prepare for something one is not expecting.

CONCLUSION

We have shown that explicit expectation affects preparatory processes and thus assumes a causal role in controlling behavior. This finding speaks against the notion of explicit expectation as a mere by-product of preparation. When we ask participants for their subjective predictions about an upcoming event they have to respond to, they are preparing for what they say (instead of telling us what they are preparing for).

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Appendix B

Study II

Kemper, M., **Umbach, V. J.**, Schwager, S., Gaschler, R., Frensch, P. A., & Stürmer, B. (2012). What I say is what I get: stronger effects of self-generated vs. cue-induced expectations in event-related potentials. *Frontiers in Psychology,* 3:562

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What I say is what I get: stronger effects of self-generated vs. cue-induced expectations in event-related potentials

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Expectations regarding future events enable preparatory processes and allow for faster responses to expected stimuli compared to unexpected stimuli. Expectations can have internal sources or follow external cues. While many studies on expectation effects use some form of cueing, a direct comparison with self-generated expectations involving behavioral and psychophysiological measures is lacking. In the present study we compare cue-induced expectations with self-generated expectations that are both expressed verbally in a within-subjects design, measuring behavioral performance, and event-related brain potentials (ERPs). Response time benefits for expected stimuli are much larger when expectations are self-generated as compared to externally cued. Increased amplitudes in both the N2 and P3 components for violations of self-generated expectations suggest that this advantage can at least partially be ascribed to greater perceptual preparation. This goes along with a missing benefit for stimuli matching the expected response only and is mirrored in the lateralized readiness potential (LRP). Taken together, behavioral and ERP findings indicate that self-generated expectations lead to increased premotoric preparation compared to cue-induced expectations. Underlying cognitive or neuronal functional differences between these types of expectation remain a subject for future studies.

Keywords: self-generated expectations, cue-induced expectations, event-related brain potentials, N2, P3, lateralized readiness potential

INTRODUCTION

Expectations play a crucial role in action control. Research on effect-based action control has stressed that representations of anticipated action effects play a role when performing an action (e.g., Nattkemper et al., 2010). According to the ideo-motor principle (see Shin et al., 2010, for a recent review) the mental representation of an anticipated action effect triggers the action (similar to forward and inverse computational models of motor control, e.g., Wolpert and Ghahramani, 2000). For instance, the representation of an open drawer might help us to initiate the pulling action. By choosing actions according to the anticipated effects, people can gain intentional control over their behavior (e.g., Kunde, 2001; Pfister et al., 2010). They can consider expectations about upcoming action effects for choosing between actions depending on which effects they desire or not. As such, expectations about effects stem from goals of the actor. They might not be directly caused by current external stimulation, but rather be self-generated by integrating goals and past external stimulation. Interestingly, this view often does not directly translate to the methodology of experiments on the role of action effect anticipation in action control. For instance, the role of anticipated effects has been studied by presenting action effects additionally as subliminal stimuli (e.g., Kunde, 2004) or irrelevant flankers (e.g., Zießler and Nattkemper, 2002). One could argue that presenting to-be-expected effects as stimuli might trade experimental control against external validity, as such a situation is not closely resembling action preparation driven by self-generated expectations. Conceivably, intentional action control supposes self-generated expectations. These are likely to interact with stimulus-based preparation but are unlikely identical to this. For instance, according to Kunde et al. (2007) actors use anticipated action effects based on internal goals. Yet, stimuli have an important role in this view, too. They disambiguate situations as to whether or not an effect can be brought about by an action. As many actions only lead to the desired outcomes in highly specific contexts, the role of a stimulus is to signal that in the current context the link between expected effect and action is valid.

Taken together, this reasoning might suggest that the presumed equivalence between self-generated expectations and cue-induced expectations cannot be taken for granted. It is also conceivable that self-generated expectations differ from expectations that are directly triggered by external stimuli or cues. A similar distinction has been discussed with respect to internally triggered vs. externally cued task switching (Arrington and Logan, 2005). Differences between expectations based on external cues and internal sources are also conceivable given the long history of debates concerning motor patterns that are predominantly stimulus-triggered vs. predominantly driven by a response goal. For instance, the Baldwin–Titchener debate at the end of the nineteenth century (e.g., Baldwin, 1895; Titchener, 1895) centered around the question of whether or not response times (RTs) are regularly shorter when people concentrate on the response rather than on expecting the stimulus. An important insight of that debate was that people can apparently choose between different modes for controlling the same motor pattern.

In line with these precursors, recent results point to differences between intentional vs. reactive action. Surprisingly, a motor pattern already triggered by an internal goal is incompatible with the execution of the very same motor pattern in response to a stimulus presented while the intentional action is in preparation (e.g., Astor-Jack and Haggard, 2005; Pfister et al., 2012). If an internally prepared action is truncated by a stimulus that requires the same action that was intentionally prepared, RT costs result in comparison to a situation where the response could be executed without concurrent intentional preparation. The authors interpret their results as evidence for distinct action systems that are triggered either endogenously by intention or exogenously by an imperative stimulus. Presenting the stimulus during intentional action preparation therefore results in interference between both systems and delays the action. In line with these results, Herwig et al. (2007) have differentiated two types of action control modes, a stimulus-based action control mode and an intention-based action mode. Pfister et al. (2011) have shown that previously acquired action effect associations either impact performance or not, depending on which of these two modes is operating. One can of course debate what exactly differentiates the intention-based from stimulus-based action mode (e.g., Neuringer and Jensen, 2010), however, empirical data highlights that different paths to action do exist.

While our current study is inspired by recent work on effect-based action control, we focus on distinguishing between self-generated vs. cue-induced stimulus expectations. Such a focus is feasible given that theories on integration of perception and action (e.g., Hommel, 2009; Magen and Cohen, 2010) suggest that action effects and stimuli share the same representational basis. Studying self-generated vs. cue-induced expectations is driven by the conjecture that anticipating appropriate environmental conditions in order to prepare for efficient goal-directed actions is one of the core abilities of our neurocognitive system (e.g., Kunde et al., 2007). Anticipation, prediction, and expectancy are only some of the labels used to discuss such mechanisms (e.g., Sutton and Barto, 1981; Elsner and Hommel, 2001; Jentzsch and Sommer, 2002). Here we use the term expectation in a broad sense, encompassing both the process of expecting as well as the object of this process. Expectations can originate from prior experience, when events occurring with a high frequency in the past are expected to be more likely to occur again in the future (e.g., Fitts et al., 1963). Expectations may as well rest upon situational cues that provide advance information about upcoming events (e.g., Posner and Snyder, 1975). Whatever the source, performance is usually boosted when the expected event occurs, whereas unexpected events impair performance (e.g., Acosta, 1982).

Previous studies of expectation have often exclusively relied on the use of external cues (e.g., Shulman et al., 1999; Oswal et al., 2007). Cueing allows a more rigid experimental manipulation of the induced expectations as compared to a setup with self-generated expectations. However, before jumping to the conclusion that cueing should be used to study expectation in general, potential functional differences between endogenous and exogenous expectations should be scrutinized. To our knowledge, the only direct comparison of self-generated and cue-induced expectations was carried out by Acosta (1982). In a series of experiments he pitted predictions verbalized by participants against cues (words that announced a certain stimulus and were to be read aloud). As he included neutral expectations as a control, he could differentiate the facilitation of correct expectations from the cost of a wrong expectation. Furthermore, he manipulated the expectation-target interval and found effects of the interval duration in the prediction condition for both benefits of matches and costs of mismatches. Benefits increased with longer expectation-target intervals while costs were highest at the shortest intervals. The effects were generally much smaller in the cue condition. Mismatch costs were also highest at the shorter intervals while no significant benefits for matches of cue-induced expectations were found. In a second experiment he manipulated the number of the response alternatives by mapping more than one stimulus to a response. The expectation effect did not increase linearly with the number of alternative responses, indicating that the process responsible for expectation effects is not just a scaling effect in choosing between the possible alternatives to predict. Moreover, his findings suggested that expectation effects were bound to stimulus processing rather than to response processing. As multiple stimuli were mapped to the same response, an expectation concerning a stimulus could be violated while the response to be executed was the same that would have been appropriate in case of a stimulus matching the expectation. Responses in such trials were as slow as those to unexpected stimuli with a different response. This suggests that the expectation effect is not (solely) a part of response execution.

Comparing different behavioral effects of self-generated vs. cue-induced expectation, Acosta (1982) concluded that the types of expectation differed only in the magnitude of their effects but not qualitatively. It therefore appears expedient to study self-generated vs. cue-induced expectations with respect to their effects on action preparation including neural measures that are more independent of the overt responses and could better differentiate quantitative from qualitative effects. In the current study we aimed to replicate the behavioral findings of Acosta (1982), showing stronger effects of self-generated compared to cue-induced expectations. Moreover, we used event-related brain potentials (ERPs) to further distinguish the contribution of different cognitive processes to expectation effects in these two conditions. This includes potential differences between the two types of expectation prior to stimulus presentation. Qualitative differences in preparatory activity would be in accordance with theories that assume different routes to action (e.g., Astor-Jack and Haggard, 2005; Kunde et al., 2007; Pfister et al., 2011).

Explicit self-generated expectations about upcoming stimuli measured on a trial-by-trial basis (through verbalization) have not been a focus of recent research. To analyze the processes during the build-up of the expectations and response preparation, we used EEG recordings. There are two main questions we wanted to address with this study. First, do differences between the expectation types already exist prior to stimulus presentation? Second, which cognitive processes (perception, action selection, motor preparation) are influenced by expectation? More specifically, do self-generated expectations affect other processes than cue-induced expectations (qualitative differences between the expectation types) or affect the same processes but with a different magnitude (quantitative differences)?

We manipulated the type of expectation within-subjects. In the prediction condition participants had to verbally express their expectation regarding the upcoming stimulus, in the cue condition they had to read aloud a word naming the upcoming stimulus. Stimuli were simple shapes or colors. The task was then to react as fast as possible to the imperative stimulus with the right or left index finger. Since there were four stimuli, with two mapped to each finger, three types of matches or mismatches existed. First, for *stimulus matches* the expected (cued or predicted) stimulus matched the upcoming stimulus. Second, for *response matches* the expected stimulus did not match the upcoming stimulus but required the same response. Third, for *mismatches* the expected stimulus and the upcoming stimulus were different and did not require the same response either.

In addition, we included a manipulation of stimulus frequency. The two stimuli mapped to each finger were shown with different frequencies, at either 33 or 17% of all trials. Both hands had to respond equally often. The frequency manipulation was included to guide the participants' predictions and to provide a measure indicating whether participants base their predictions on their experience (instead of random guessing). In a similar paradigm, Umbach et al. (2012) have shown that participants closely match their stimulus predictions to the observed frequencies. Even though expectations in their study were not valid in predicting the stimulus (similar to the current study) participants nonetheless used these expectations in preparing their responses.

The role of expectation in action preparation can be studied by comparing trials in which upcoming stimuli fulfill vs. do not fulfill expectations in behavioral measures (RTs and errors, e.g., Acosta, 1982) or with regard to effects in the brain that can for instance be measured by EEG (e.g., Matt et al., 1992; Jentzsch and Sommer, 2002). There are multiple processes that can lead to the expectation mismatch effects. It is possible that a correct expectation (a) facilitates the encoding of the stimulus, (b) the response selection, (c) response execution, or a combination of these. It is also possible that an expectation that does not match the stimulus delays one of these processes, or else that both – fulfilled and unfulfilled expectations – have opposing effects. Time differences in RTs and the latencies of the different ERPs which occur during the different stages prior to the response can help to show the stage(s) where the expectations exert their influence. ERP amplitudes can provide information about the magnitude of the involved processes in the different conditions.

CONTINGENT NEGATIVE VARIATION

To investigate whether there is a difference of cue-induced vs. self-generated expectation even before the stimulus is shown, we charted the contingent negative variation (CNV). This is a slow negative potential following an event cueing the upcoming target stimulus (inducing expectations in our case). The CNV develops in the cue-target interval and its amplitude is most pronounced directly before onset of the imperative stimulus. Depending on task demands, the late phase of the CNV reflects sensory, cognitive, or motor preparation (Damen and Brunia, 1994; Fan et al., 2007). Acosta (1982) has shown stronger RT effects in self-generated as compared to cue-induced expectations. A possible cause of this difference may be that the internal generation of expectations results in a larger amount of specific preparation that could, consequently, show up in a more pronounced CNV in the prediction condition.

N2

The N2 is an ERP characterized by a larger amplitude in cases where the stimulus deviates in form or context from the prevailing stimulus (for a review, see Patel and Azzam, 2005). The N2 is also larger in response conflict trials as evoked by incongruent flanker or no-go trials (Kopp et al., 1996). Therefore, we explored whether mismatch between either kind of expectation and the upcoming target would result in an enlarged N2 amplitude. Larger interference effects in the N2 have been demonstrated in the Eriksen flanker task with a greater proportion of incongruent trials (Tillman and Wiens, 2011). As the interference effect on RTs was smaller in this condition, the N2 might reflect endogenous attention processes. If we assume that self-generated expectations have a stronger influence on preparatory processes (e.g., attention), the violation of an expectation might result in a larger N2 effect in the prediction condition compared to the cue condition.

P3

Matt et al. (1992) and Jentzsch and Sommer (2002) differentiated between passive and active forms of expectations. While passive expectations automatically affect behavior, active expectations act in a rather controlled manner (Kahneman and Tversky, 1982). Matt and colleagues induced active expectations through instruction ("Expect stimulus repetitions!" "Expect stimulus alternations!") in a blockwise manner. P3 amplitude as well as RTs revealed the higher order repetition effects typically found in simple reaction time tasks (stimulus repetitions benefit if they continue a run of repetitions, alternations if they continue a run of alternations). Importantly, the RT effect but not the P3 effect was modulated by the instructed expectation (expecting repetitions reduced the sequential effect for repetitions and increased that for alternations, and vice versa). This dissociation suggests that active and passive forms of expectation differentially affect processing stages involved in performing the task but might not show up in the P3.

However, operationalization of active and passive forms of expectation differed between Matt et al. (1992) and the current study. In contrast to their experimental approach, self-generated expectations in the current study were allowed to change on a trial-by-trial basis and were induced by stimulus frequency. Self-generated expectations might lead to stronger P3 effects as compared to cue-induced effects, because generating expectations internally trial-by-trial might lead to more pronounced processing of the expectation as compared to reading a cue. If one considers the relation of stimulus to expectation (rather than considering the stimulus alone), there are various possibilities for P3 effects. On the one hand, it is possible that the P3 relates to expectation by capitalizing on stimulus probability. In the current design, expectations often mismatch the actual stimuli. Even if a participant exclusively relies on the frequent stimulus, expectation matches are rare. Therefore, upon stimulus presentation, a P3 could follow in case of matches. On the other hand, P3 may reflect the accuracy of a concrete expectation on a single-trial basis rather than reflecting the past frequency of this expectation being fulfilled. In this case, a stimulus mismatching the expectation should elicit the higher P3 amplitude.

LATERALIZED READINESS POTENTIAL

At the other end of the processing stream, the lateralized readiness potential (LRP) can be used to infer the role of response preparation in expectation effects (e.g., Jentzsch and Sommer, 2002). The LRP is a difference waveform that arises with a higher activity in the motor area of the brain hemisphere contralateral to the responding hand as compared to the ipsilateral hemisphere (Coles, 1989). The onset of the stimulus-locked LRP (S-LRP) provides a chronometric index of premotor processing stages (Leuthold et al., 1996) while onset differences in the response-locked LRP (LRP-R) indicate processing differences at late motor-related stages (Hackley and Valle-Inclán, 1998). Jentzsch and Sommer (2002) found that S-LRP was significantly influenced by the expectations, while the LRP-R was not. This shows that the instructed expectation influenced a process after early stimulus processing (as P3 was not affected in this study) but prior to the response initiation. Accordingly, we assumed expectation effects specifically on the S-LRP that should be particularly strong in case of self-generated expectations.

INFLUENCES OF STIMULUS FREQUENCY

While the main focus of our experiment lay on the comparison of cue-induced vs. self-generated expectations, the variation of stimulus frequency we applied also needs to be briefly summarized. Obviously the experimenter has little control over expectations self-generated by participants. By varying stimulus frequency it should be possible to partly shape self-generated expectations and to be able to explore how self-generated expectations accommodate to the task environment (see Umbach et al., 2012). Specifically, reliance on stimulus frequency can be considered a sign of subjective validity of the self-generated expectations that participants are asked to verbalize. Furthermore, the more frequent stimuli should lead to faster responses as compared to less frequent stimuli. Potential effects of stimulus frequency may in part be independent of expectation match effects in the current trial (compare Jiménez and Méndez, 2012). Conceivably, stimulus frequency leads to a sustained effect more similar to the passive form of expectation that Matt et al. (1992) found reflected in the P3. We expected larger P3 and N2 components for infrequent as compared to frequent stimuli.

Furthermore, the CNV is seen to reflect preparatory processes and the amplitude is, for example, modulated by cue validity (if the upcoming stimulus is specified with different probabilities). CNV amplitude is larger the more valid the cues (and thus, the more expected the stimuli) are (Scheibe et al., 2009). We therefore expect a larger CNV for the expectations of frequent stimuli since these are more likely to be fulfilled (33 vs. 17% validity).

MATERIALS AND METHODS

PARTICIPANTS

Eighteen participants (four men) with a mean age of 24.7 years took part in the experiment. All Participants were right-handed and had normal or corrected-to-normal vision. The participants were either psychology students at Humboldt-Universität zu Berlin and participated in exchange for course credit or received a compensation of €20 for the experiment with a duration of approximately two and a half hours. Participants gave their informed consent prior to the experiment.

APPARATUS AND SOFTWARE

The Experiment was programmed with MathWorks MATLAB and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) and presented on a Windows computer. The participants' expectations were recorded using a table microphone and played to the experimenter who coded the predictions on a separate computer outside the EEG booth. Error feedback after erroneous responses was given via tabletop speakers.

STIMULUS MATERIAL AND EXPERIMENTAL MANIPULATION

The stimuli were either simple shapes (house, star, cross, and gate) or colored circles (blue, red, green, and yellow) presented on a computer monitor with a light gray background. Stimuli were 22 mm in diameter, corresponding to a visual angle of about 2.1° at a viewing distance of approximately 60 cm. The experiment consisted of two parts: a cue-induced (cue condition) and a self-generated expectation variant (prediction condition). One of these parts was performed with colors as stimuli and the other with shapes. The order of the expectation variants as well as the assignment to the two types of stimuli was randomized across participants.

In trials of the cue condition, the participants were presented with the one-syllable word for one of the stimuli, which they were instructed to read aloud (the German equivalents for house, star, cross, and gate in the shape condition, or the German equivalents for blue, red, green, and yellow in the color condition). In the prediction condition they saw a prompt – the German equivalent for "color?" or "shape?" – to which they should respond by naming the stimulus they expected to appear in the current trial. Thus, verbal output consisted of the same words in both expectation conditions.

Participants had to react to the stimuli by pressing one of two buttons with either the left or the right index finger. Depending on the current type of stimuli, each button corresponded to two forms or two colors. The mapping was randomized, shown before the experiment and was trained during two training blocks. Of the two stimuli per hand, one was presented in one out of three trials (33% = frequent stimuli) and the others in one out of six (17% = infrequent stimuli; half as often as the frequent stimuli), together resulting in the same frequency (50%) of responses with each hand. The order in which the stimuli were presented was randomized. In the cue condition, the frequency of the cues was matched to the frequency of the stimuli (cues for frequent stimuli were shown in 33% of the trials, cues for infrequent stimuli in 17%). The task is shown in **Figure 1**.

TASK PROCEDURE AND INSTRUCTIONS

After being introduced to the lab and the experimental procedure, participants provided their consent to participate and were seated in a one person lab room and prepared for the EEG measurements. Next a detailed explanation of the task in the following

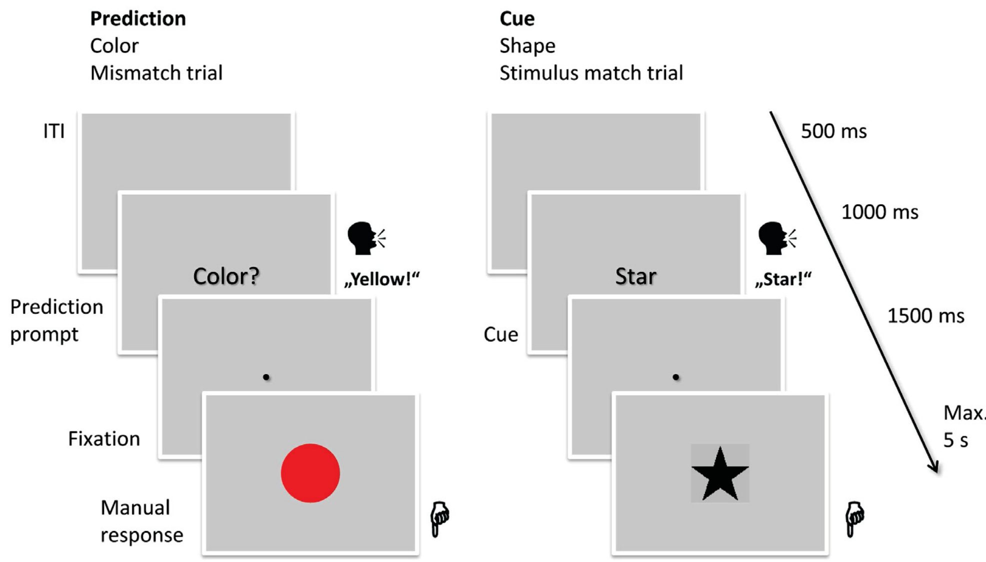

FIGURE 1 | Task used in the experiment. On each trial, participants either had to read aloud the cue (in this case "star") or to verbalize their prediction for the upcoming stimulus (in this case "yellow"). After 1,000 ms the fixation point appeared on screen and after another 1,500 ms the stimulus appeared on screen (in this case red in the prediction trial, signifying a mismatch, and a star in the cued trial, signifying a match). The participants manually responded to the stimulus by pressing one of two keys. The next trial started 500 ms after the response. The mapping of the stimulus types (shape, color) to the expectation conditions and the order of the expectation conditions was balanced over participants.

experiment and the stimulus-response mapping was presented on the screen and also explained by the experimenter. Instructions explained the course of the trials, the response mappings and the request to relax the mouth as soon as possible after pronouncing the expectation (i.e., as soon as the fixation point presented in response to the registration of the expectation). This was included to ensure minimized muscle artifacts in the EEG measurements.

The first training block of eight trials followed. After that, a shorter version of the instructions was presented and any questions that arose during the first training block could be clarified with the experimenter. This was followed by another training block, after which the experimenter left the room and the participant could start the experiment by pressing a button. The experiment consisted of two parts, each containing five blocks of 108 trials. The length of the breaks between the blocks could be controlled by the participants. The second half of the experiment contained a switching of the stimuli and expectation condition. There were again two training blocks of eight trials each preceded by instructions explaining the new task. To minimize mistakes, the stimulus-response mapping was shown before every block. If the wrong button was pressed an acoustic error feedback was given; it was also given when no button had been pressed within 5 s following stimulus presentation.

Each trial in the experimental blocks began with the presentation of either the cue or the prompt for the expectation in the middle of the screen. After 1,000 ms, the fixation point was shown at the same point. After another 1,500 ms, the stimulus was shown until a button press was registered or for 5 s if no reaction followed during that time. This was followed by an intertrial interval of 500 ms before the next trial started with the presentation of a cue or prediction prompt.

At the end of the session participants were asked to estimate the frequency of the characteristic stimulus values.

ELECTROPHYSIOLOGICAL RECORDINGS

Recordings were made from Ag/AgCl electrodes mounted in an electrode cap (Easy-Cap) at 25 scalp positions (FP1, FP2, F3, F4, F7, F8, C3, C4, T7, T8, P3, P4, P7, P8, O7, O8, O1, O2, FPz, Fz, FCz, Cz, CPz, Pz, Oz) according to the extended 10–20 system. AFz served as ground electrode. In addition, external electrodes were used for recording the vertical and horizontal electrooculogram as well as for the mastoids. The electrodes were referenced to the linked mastoids. Electrode impedance was kept below 5 kΩ. The EEG was recorded with a sampling rate of 1,000 Hz and no online filters were applied. Blink artifacts were corrected semi-automatically by independent component analysis (ICA) using the ICA algorithm integrated in the BrainVision Analyzer 2.0 (BrainProducts GmbH). Offline, the continuous EEG was separated into individual trials with 300 ms pre- and 2,700 ms post-cue epochs (cue-locked data, in the prediction condition they were locked to the presentation of the prompt), and 200 ms pre- and 800 ms post-stimulus epochs (stimulus-locked data), and with 1,000 ms pre- and 200 ms post-response epochs (response-locked data).

DATA ANALYSIS

For data analysis, only trials with correct key presses were considered. For the CNV, the cue-locked segments were averaged according to the expectation condition (cue vs. prediction) and frequency condition (expectation corresponded to frequent or infrequent stimulus) and 30 Hz low-pass filtered. For the statistical analysis the difference between the mean voltage around the visual potential of the fixation point (1,400–1,200 ms prior to stimulus presentation) and the mean voltage 200 ms before the stimulus onset at electrode Cz was used with the baseline 200 ms before the onset of the cue or the prediction prompt. For the N2 and P3, the stimulus-locked segments were averaged according to the expectation conditions (cue vs. prediction) and match types (mismatch, response match, and stimulus match) and 30 Hz low-pass filtered (Butterworth, slope 12 dB/oct). The N2 amplitude was the mean amplitude measured at Fz between 250 and 350 ms after stimulus onset. P3 latency was measured as the time of the positive maximum at the Pz electrode during the time range of 250–550 ms following stimulus onset. The P3 amplitude was measured as the mean amplitude measured at Pz between 250 and 550 ms after stimulus onset. For both N2 and P3 the baseline was taken during a 200 ms pre-stimulus interval.

For the LRP, EEG was 5 Hz low-pass filtered (Butterworth, slope 12 dB/oct). The LRP was derived by computing difference waves for the C3 and the C4 electrodes between the electrode contralateral to the corresponding hand in a given trial and the ipsilateral electrode. Then the two types of difference waves (C3–C4 for right-hand response trials and C4–C3 for left-hand response trials) were averaged within each of the experimental conditions (cue mismatch, cue response match, cue stimulus match, prediction mismatch, prediction response match, prediction stimulus match). LRP onsets were analyzed using a jackknife-based procedure for factorial designs (Ulrich and Miller, 2001). Eighteen different grand average LRPs for each of the experimental conditions were computed by omitting the ERP data of one participant from each grand average. This allowed to measure the usually noisy LRP onsets much more precisely than on a single participant. LRP onsets were measured in the waveform of each grand average and submitted to an ANOVA with F-values corrected as $F_c = F/(n-1)^2$, with F_c as the corrected F-value and n as the number of participants. S-LRP onsets were measured with a 200 ms pre-stimulus baseline and LRP-R with a 100 ms baseline, starting 100 ms after the responses were made. As Miller et al. (1998) recommended, we used a relative criterion of 50% of the maximal LRP amplitude during the recording epoch for determining the LRP onsets for both the S- and the R-locked LRPs.

SPEECH ARTIFACTS AND VERBALIZATION LATENCY

The participants were asked to verbalize their expectation as soon as the prompt or cue was shown and to relax their facial muscles again as soon as the fixation point was shown. The EEG data acquired during the time of speech was not analyzed. The earliest data points used in the analysis were in the Cz amplitude (CNV), starting 100 ms after the presentation of the fixation point, which should render enough time for artifacts from muscles involved in the prior speech production to subside. Visual inspection of the microphone recordings showed activations in the frequency range of speech primarily prior to the presentation of the fixation point. In addition, the stimulus types and their mapping to the expectation condition and frequencies were randomized; thus their verbalization should not have been able to systematically influence any EEG measurements. Furthermore, participants were instructed to use the relatively long interval between the prompt or cue and the fixation point for blinking if necessary.

Analyzing processing differences with chronometric measures (as comparing ERP latencies) presumes equivalent starting points of the processes of interest. In our case it is assumed that possible preparatory processes start with the verbalization of either the prediction or the cue, respectively. Possibly, however, it is harder to generate a prediction than to read a cue. If, because of this, predictions are verbalized later than cues that have simply to be read aloud, preparation, on the one hand, may start later in the prediction condition and, on the other hand, the distance in time between the verbalization and the imperative stimulus would be shorter for predictions than for cues. Both influences would make a comparison of the time courses of the prediction and cue conditions problematic. Being aware of these difficulties we conducted a behavioral pilot study with the same materials that allowed a precise measurement of voice onset times. Moreover, anticipating possible differences in verbalization latency, we locked the time of stimulus presentation in this pilot study to voice onset time rather than using a fixed interval between prompt/cue and stimulus as in the main study reported here. The stricter controlled pilot study revealed the same behavioral effects of expectation as the EEG study. Importantly, we found no difference in verbalization latency between predictions and cues (though the different standard deviations may mirror a processing difference between producing one and the same word as a prediction or by reading)[1] and decided for a fixed interval between prompt/cue and stimulus in the main study in order to avoid problems with incompatibilities between speech recognition and precise EEG recording.

RESULTS

EXCLUSION OF DATA

Training blocks were not analyzed. Furthermore, error trials were excluded from the RT and EEG analyses. Trials in which the participants had not reacted after 5 s were counted as error trials. According to this criterion 2.6% of all trials were excluded. Response time analyses were based on medians per participant and condition. Due to the experimental design, roughly twice as many mismatch trials went into the analysis compared to response matches and stimulus matches; this proportion was similar for both expectation conditions[2]. Predictions were matched by the correct stimulus in 25.9% of trials while cues were valid in 27.7%.

BEHAVIORAL DATA

Response times and error rates can be seen in **Figure 2**. RT was on average 72 ms longer for mismatches than for stimulus matches. This slowing was about the same for response match and complete mismatch trials. Match trials were also more accurate than mismatch trials. The advantage of stimulus matches was larger for the prediction condition (**Figure 2**, left; 113 ms) than for the

[1]Voice onset time results from the behavioral pilot study; predictions: $M = 467$ ms (SD = 117.03), cues: $M = 465$ ms (SD = 49.05), $t(9) = 0.08$, ns.

[2]Number of trials, excluding errors: predictions: mismatch $M = 257$ (SD = 13); response match $M = 127$ (SD = 11); stimulus match $M = 138$ (SD = 11); cues: mismatch $M = 268$ (SD = 7); response match $M = 119$ (SD = 5); stimulus match $M = 149$ (SD = 4).

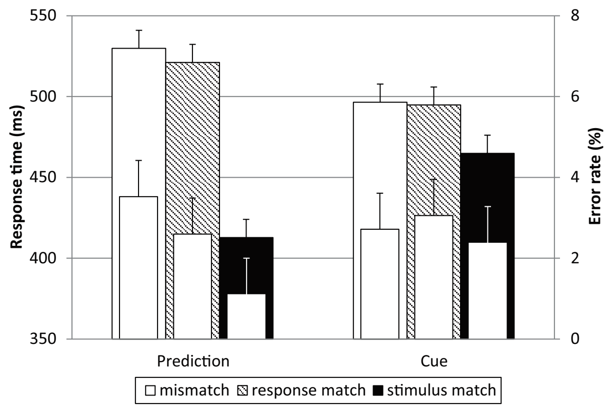

FIGURE 2 | Response times and error rates. Response times (outer bars) exhibit an effect of match (with faster responses to stimulus matches than to response matches and mismatches) and an interaction with expectation condition (with a stronger effect of match in the self-generated predictions, left). The same pattern is visible in the error rates (inner bars). There were less errors made in the match trials, thus the effect in response times cannot be explained by a speed-accuracy trade-off. Error bars represent confidence intervals (95%) for repeated-measures designs according to Loftus and Masson (1994) and Jarmasz and Hollands (2009).

cue condition (**Figure 2**, right; 31 ms). Additionally, the RTs were 17 ms shorter for the frequent stimuli compared to infrequent stimuli. A three-way repeated-measures ANOVA with expectation condition, match and frequency as within-subjects factors on the median RTs rendered a significant main effect of frequency, $F(1, 17) = 32.96$, $p < 0.001$, $\eta_p^2 = 0.66$, and of match, $F(2, 34) = 316.38$, $p < 0.001$, $\eta_p^2 = 0.95$; there was no main effect of expectation condition, $F(1, 17) = 0.06$, ns. Importantly, there was a significant interaction of match and expectation condition, $F(2, 34) = 36.78$, $p < 0.001$, $\eta_p^2 = 0.68$, with a larger difference between the two types of mismatch and the stimulus match for the prediction condition than for the cue condition. T-tests revealed that for both expectation conditions there was no significant difference between mismatch and response match [both $t(17) < 1.46$, ns], while the stimulus match was significantly faster than both [all $t(17) > 6.69$, $p < 0.001$, all $d > 3.38$]. The effect of match on the error rates was in the same direction, $F(2, 34) = 7.13$, $p = 0.003$, $\eta_p^2 = 0.30$, with less errors for stimulus matches as compared to mismatches. The effects can therefore not be explained by a speed-accuracy trade-off.

The frequency manipulation was reflected in the prediction behavior, as participants predicted the more frequent stimuli on a larger proportion of trials, $\chi^2(1) = 7.39$, $p = 0.007$. The *post hoc* estimates of stimulus occurrence in % made by the participants also provide a good approximation of the actual frequencies, with the frequent stimuli at 59%, and the infrequent stimuli at 41% (for comparison, real presentation frequencies: 66 and 33%, respectively).

CONTINGENT NEGATIVE VARIATION

The CNV was neither influenced by the expectation condition nor by the frequency. A repeated-measures ANOVA for the influence of frequency and expectation condition revealed no main effect of expectation condition, $F(1, 17) = 1.29$, ns, or of frequency, $F(1, 17) = 1.64$, ns, and no interaction, $F(1, 17) = 0.92$, ns.

N2

Figure 3 (top) shows the N2 for the prediction and the cue condition at electrode Fz. The N2 amplitude was larger for the cue condition than for the prediction condition, and in both expectation conditions the N2 was larger for mismatches and response matches than for stimulus matches. The amplitude difference of response matches and mismatches compared to stimulus matches was larger for the prediction than for the cue condition. A repeated-measures ANOVA for the effects of match type and expectation condition on the mean amplitude of the N2 measured at Fz between 250 and 350 ms revealed a main effect for match, $F(2, 34) = 15.52$, $p < 0.001$, $\eta_p^2 = 0.48$ and a main effect for expectation condition, $F(1, 17) = 39.14$, $p < 0.001$, $\eta_p^2 = 0.70$. The interaction was based on a larger amplitude difference between the different match types for the prediction condition compared to the cue condition, $F(2, 34) = 6.79$, $p = 0.003$, $\eta_p^2 = 0.29$. A three-way repeated-measures ANOVA that also included the influence of frequency on the N2 peak amplitude rendered no main effect of frequency, $F(1, 17) < 0.01$, ns.

P3

The P3 (**Figure 3**, bottom) had a larger amplitude for predictions compared to cues and for mismatches compared to stimulus and response matches. In the cue condition the full stimulus match exhibited the smallest P3 amplitude, with a higher amplitude for response matches and the highest amplitude for mismatches. In the prediction condition the pattern was more complex, with stimulus matches showing a much shorter peak latency of the P3 compared to all other conditions. A repeated-measures ANOVA for the effects of match type and expectation condition on the mean amplitude of the P3 revealed a main effect for match, $F(2, 34) = 14.16$, $p < 0.001$, $\eta_p^2 = 0.45$, a main effect for expectation condition, $F(1, 17) = 16.23$, $p < 0.001$, $\eta_p^2 = 0.49$, and a significant interaction, $F(2, 34) = 6.83$, $p < 0.003$, $\eta_p^2 = 0.29$. A three-way repeated-measures ANOVA that also included the influence of frequency on the P3 mean amplitude rendered no effect of frequency, $F(1, 17) = 0.23$, ns. There was a significant effect of match on the peak latency, $F(2, 34) = 17.20$, $p < 0.001$, $\eta_p^2 = 0.50$. A t-test revealed that this was due to the earlier P3 for stimulus matches in the prediction condition. The P3 for stimulus matches in the prediction condition began on average 85 ms earlier than for mismatches, $t(17) = 5.57$, $p < 0.001$, $d = 2.70$.

LATERALIZED READINESS POTENTIAL

The onset of the S-LRP was earlier for stimulus matches than for response matches and mismatches, mirroring the RT results (**Figure 4**, top). A repeated-measures ANOVA for the influence of match and expectation condition on the S-LRP onset rendered a main effect of match, $F(2, 34) = 24.33$, $p < 0.001$, $\eta_p^2 = 0.59$, but not of expectation condition. There was a trend toward an interaction, $F(2, 34) = 2.58$, $p = 0.090$, $\eta_p^2 = 0.13$, with a larger difference between the S-LRP onset latency for the stimulus match compared

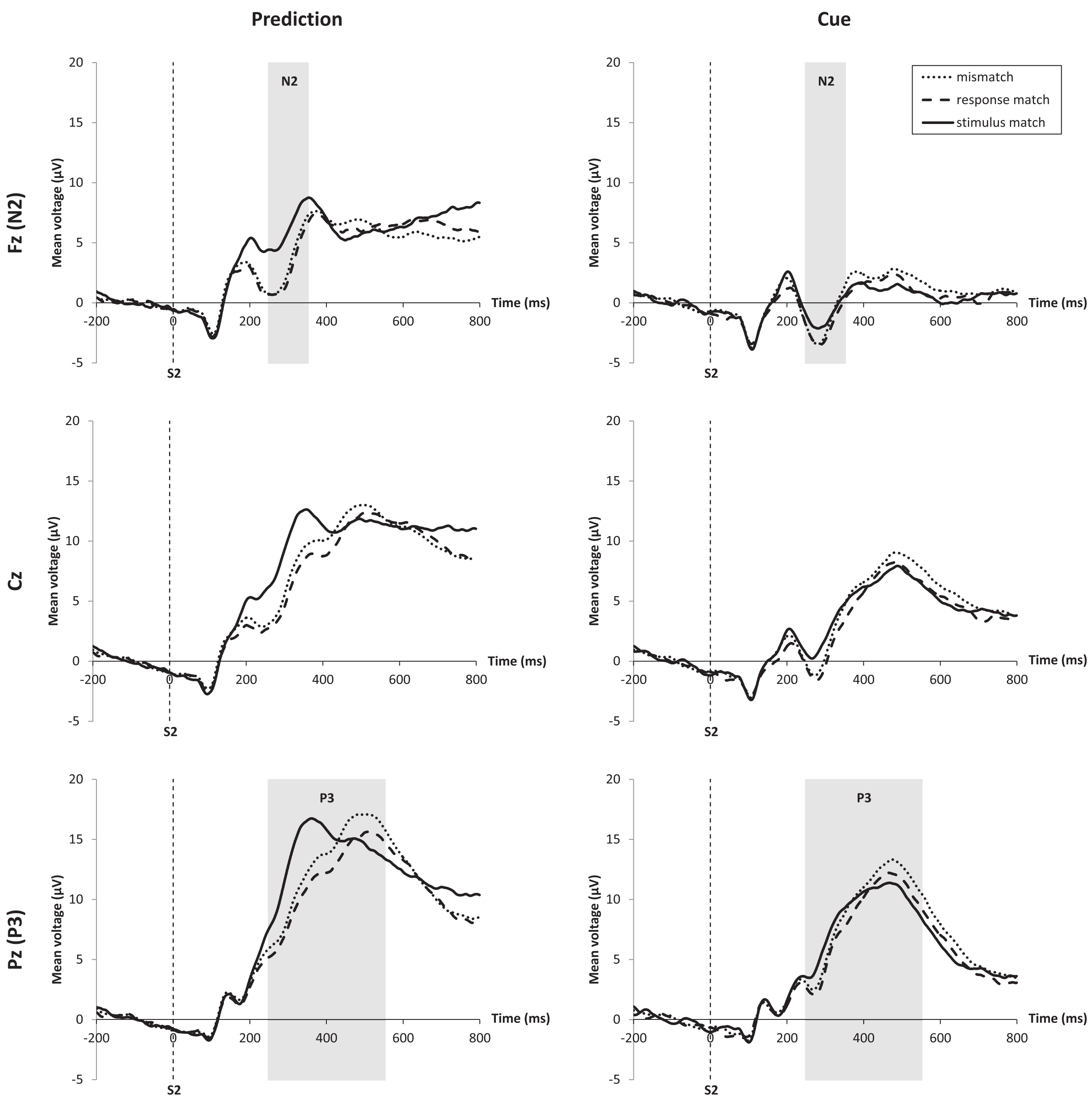

FIGURE 3 | ERPs at midline electrodes Fz, Cz, and Pz time-locked to stimulus onset. Prediction condition is shown on the left, cue condition on the right. For each electrode the different waveforms for the three match types are shown. Analysis windows for N2 and P3 components are highlighted in gray. Stimulus matches are marked by the solid line, response matches by the dashed line, and mismatches by the dotted line. The interaction of match and expectation condition can best be seen at the Fz electrode for the N2 and at the Pz electrode for the P3.

to the response match and mismatch in the prediction condition compared to the cue condition.

As can be seen in **Figure 4** (top) there was an early rise of the response match S-LRP (especially in the prediction condition) which then soon aligned with the mismatch S-LRP. According to this visual inspection we also analyzed the average S-LRP amplitude 150–250 ms after stimulus onset. A repeated-measures ANOVA for the influence of match and expectation condition on the S-LRP amplitude 150–250 ms after stimulus onset revealed a main effect of match, $F(2, 34) = 19.44$, $p < 0.001$, $\eta_p^2 = 0.53$, but not of expectation condition. There was a significant interaction of expectation condition and stimulus match condition, F(2,

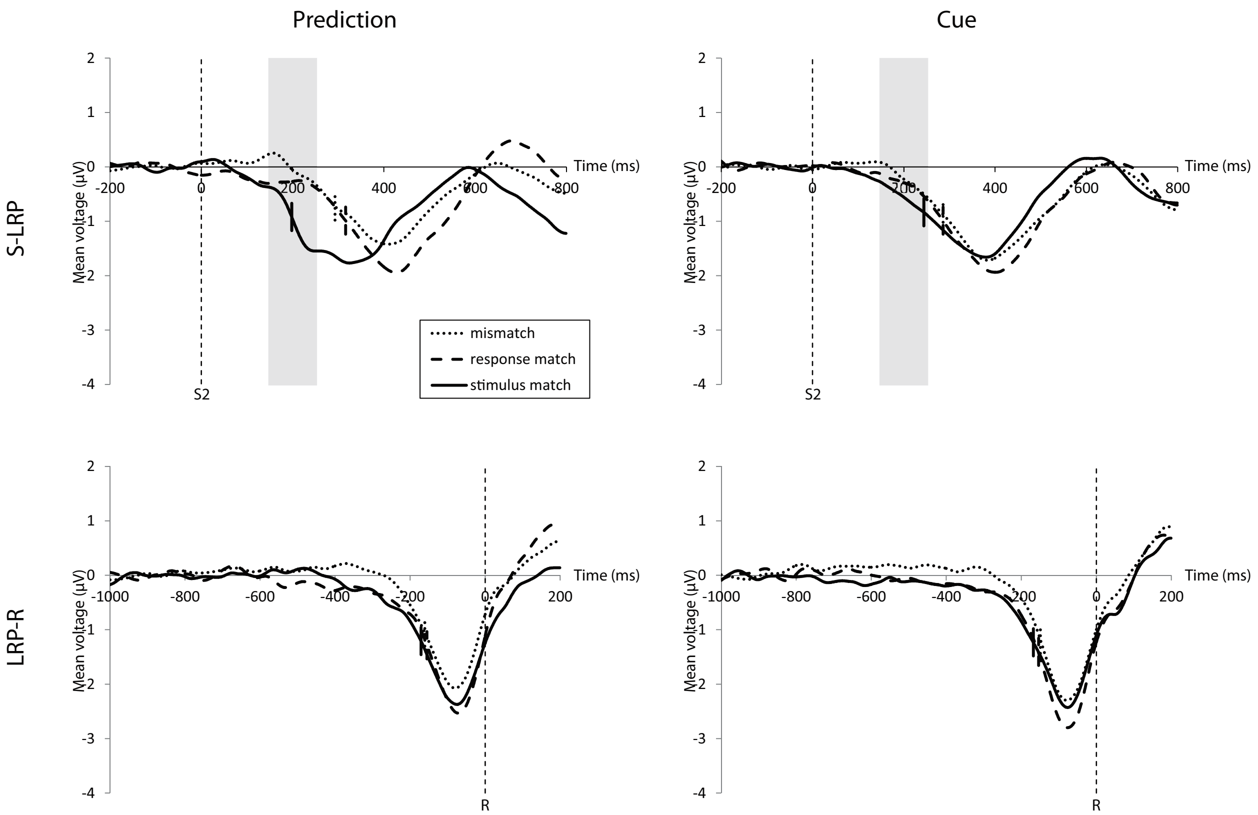

FIGURE 4 | Top: stimulus-locked LRP waveforms for the prediction condition (left) and cue condition (right). There was an earlier S-LRP onset for stimulus matches than for mismatches and response matches. (Onsets are marked by the short vertical lines intersecting the waveforms.) This onset difference was, in trend, larger for the prediction condition. Although the response match S-LRP onset is as late as for mismatches, they differ in their amplitude before S-LRP onset (50% of the maximum amplitude) in the time interval 150–250 ms following stimulus onset (highlighted in gray). The response match amplitude rises in the correct direction as with the stimulus match and is significantly higher than the mismatch amplitude, but only in the prediction condition. Bottom: response-locked LRP waveforms for the prediction condition (left) and cue condition (right). There is only a significant effect of match with an earlier LRP-R onset for stimulus matches compared to response matches and mismatches.

34) = 3.92, $p = 0.029$, $\eta_p^2 = 0.19$. The average S-LRP amplitude in the prediction condition in this interval was 0.29 µV higher for response matches than for mismatches, $t(17) = 2.20$, $p = 0.042$, $d = 1.06$ but there was no such difference in the cue condition, $t(17) = 0.65$, ns. Even though it was not reflected in the response time this finding indicates an early correct motoric activation for response matches in the prediction condition.

The onset latency of the LRP-R was influenced only by match, $F(2, 34) = 5.21$, $p = 0.011$, $\eta_p^2 = 0.24$ but not by the expectation condition; there was no interaction (**Figure 4**, bottom).

DISCUSSION

The aim of the present study was to shed some light on the basic processes that underlie the effects of expectation on the control of performance. We were especially interested in distinguishing between the consequences of self-generated expectations (predictions) vs. cue-induced expectations. On each trial participants verbalized an expectation prior to stimulus onset in a two-choice discrimination task. The expectation was either freely generated by the participants (prediction) or specified by an external cue (a word denoting the discriminating stimulus feature). Our results suggest that when investigating effects of explicit expectation one should be aware of possible differences between internally and externally triggered anticipation processes: predictions showed stronger behavioral effects and stronger effects on most ERP components after stimulus presentation that are related to expectation. The two types of expectation showed different aftereffects once a matching or mismatching stimulus was presented. Predictions, therefore, differed substantially from cue-induced expectations.

Direct comparisons of behavioral and neuronal indicators between expectations induced by cues vs. self-generated expectations have been lacking so far. With respect to behavioral differences between the two types of expectation we replicated Acosta (1982). RTs were slower when the stimulus did not match the expectation as compared to a match. This difference was larger in the prediction than in the cue condition. Moreover, as in Acosta's study, we found no benefit of response match trials over complete mismatch trials, suggesting that the expectation exerts its influence before response preparation. The results of error rates reflected RTs, contradicting a speed-accuracy trade-off. Additionally, as a consequence of the frequency manipulation in our experiment, participants also responded faster to the more frequent stimuli.

In the following we shall first discuss the relevant aspects of the ERP results on self-generated vs. cue-induced expectations. We shall then discuss how type of expectation might relate to similar distinctions in other aspects of action control.

STRONGER ERP EFFECTS FOR PREDICTIONS VS. CUES

The CNV did not reveal any differences between predictions and cues. If at all, differences in the cue-target interval between both conditions showed up in an early time window starting 450 ms after cue onset. This was, however, the time window comprising the speech artifacts. Furthermore, participants were instructed that blinks should be synchronized with speaking aloud. Although the time window of this cue-related positive deflection resembled those found in task switching paradigms (e.g., Nicholson et al., 2005; Li et al., 2012) we refrain from further interpretation until this positivity is replicated in a design excluding artifacts.

In the ERPs related to stimulus processing we found differences with respect to expectation match that were modulated by the source of expectation (prediction vs. cue). The N2 amplitude for response match and complete mismatch trials was larger than for stimulus match trials, and this difference was significantly larger in the prediction condition. The N2 has been reported to be larger for incompatibly cued stimuli (Kopp et al., 1996) and interpreted as reflecting cognitive control functions concerning incorrect response preparations. Thus, our results might reflect the need to control the prepared incorrect responses for stimulus mismatch trials. However, in case of a response match the response associated with the unexpected stimulus is correct in our experiment. Our finding of equal N2 amplitudes for response match and complete mismatch trials indicates that the control processes are triggered by the pure stimulus mismatch. This corresponds to the view that interprets the N2 as a sign of mismatch or conflict detection (e.g., Folstein and Van Petten, 2008; Nigbur et al., 2011). Our data suggests that the effect is elicited by the stimulus violating the expectation rather than by the response associated with a different stimulus than the one presented.

Expectation effects on the N2 are larger in the prediction condition. As the probability of a violation of the expectation was comparable for the prediction and the cue conditions it is unlikely that the match effect in the N2 mirrors just the probability of conflict. This finding corresponds to the view that preparing for a self-generated prediction involves endogenous attention processes to a greater degree as preparing for a cued stimulus. Furthermore, the N2 amplitude was generally higher in the cue condition. Though this main effect does not relate to our hypotheses, one might speculate that it possibly also reflects the "expectation mode" (self-generated vs. externally triggered). Presumably, expectations were weaker in the cue condition so that stimuli were generally "less expected" as compared to the prediction condition. This corresponds to the smaller expectation effects we found for the cue condition in the behavioral data and the other ERPs.

We obtained an interaction of match and expectation condition for the P3 amplitude. While usually higher P3 amplitudes have been found for infrequent stimuli (Fabiani et al., 1987), we were able to demonstrate a frequency-independent influence of subjective expectation on the P3. Our results differ from those of Jentzsch and Sommer, 2002, who did not find an influence of explicit expectation on the P3. A possible reason for this discrepancy may lie in methodological differences. In contrast to Jentzsch and Sommer, 2002; see also Matt et al., 1992), we allowed expectations to fluctuate on a trial-by-trial basis instead of manipulating them by instruction at a block-level. Inducing an expectation at the beginning of a block of trials might lead to a situation where this expectation is implemented for action preparation early on and afterward might be effective in action preparation on lower levels of representation while no longer being strongly represented as an expectation proper (compare e.g., Wenke et al., 2009, for a similar argument with respect to the implementation of instructed stimulus-response links). Furthermore our experimental approach differed from the one in the above studies in that we required participants to generate explicit expectations themselves instead of being asked to hold a specific expectation given by instructions. As a consequence, the design of the present study might have been more sensitive to detecting small effects on P3 amplitudes. Concluding from our data, we suggest that explicit self-generated expectation indeed affects early stimulus processing stages, even stronger so than cue-induced expectations.

There was a much earlier P3 peak for stimulus matches as compared to mismatches in the prediction condition. Though the component was similar in its form to the other experimental conditions, conceivably, some kind of signal of prediction success or affirmation might have played a role if the self-generated expectation proved to be correct. Usually, the latency of the P3 peak reflects the time of uncertainty resolution. Sutton et al. (1967) showed this for match trials in an experiment with explicit self-generated expectations about upcoming auditory stimuli (either single or double clicks). They analyzed match trials in which single clicks were expected. The P3 latency depended on the latency of the possible (unexpected) second click. In the conditions with earlier second clicks the P3 was also earlier because the uncertainty about whether the expectation matched could be resolved earlier. This does not explain why in our study the P3 is so much earlier for stimulus matches only in the prediction condition, while in the cue condition the P3 is as late for stimulus matches as for mismatches. In the cue condition, uncertainty regarding the correctness of preparation should be resolved similarly early as in the prediction condition. However, in accordance with the idea that self-generated expectations result in more preparation than cue-induced expectations, a stronger impact of uncertainty resolution in the prediction condition seems plausible. We looked at the scalp distribution for this component in order to check if there is an additional process responsible for the latency difference, but the distribution did not differ from the distributions around the P3 for the other conditions.

Furthermore, we found no frequency effect for the N2 or P3. Even though frequency affected RTs, these effects do not seem to stem from the processes involved in the generation of the N2 or P3. In contrast to our hypothesis and the results from Jentzsch and Sommer (2002), the more passive form of expectation generated by the stimulus frequency had no effect on the ERPs. This could be due to the relatively small frequency differences of the four stimuli. As the expectations for the more frequent stimuli in our experiment happened to be matched by the stimulus more often than for the infrequent stimuli, an effect of frequency or an interaction of frequency and condition could also have been expected to influence the CNV. Expectation validity has been shown to affect CNV amplitude (Scheibe et al., 2009). However, there were no effects of the frequency manipulation on the CNV in our data, perhaps due to the relatively small differences in stimulus frequency that resulted in equally small differences in expectation validity. Although two of the four possible stimuli were shown twice as often as the other two, the absolute difference in validity between frequent and infrequent stimuli amounted to only 17% (as compared to 25% differences and an overall higher validity, 50 vs. 75 and 100%, in Scheibe et al., 2009).

The LRP results only partially reflect our predictions. As expected, the S-LRP onset reflected the RT results for the different match types, showing that these effects are the result of premotoric processing stages. The interaction with the influence of the expectation condition only approached significance. In contrast to our hypothesis and the results of Jentzsch and Sommer (2002) there was a significant effect of match type on the LRP-R onset, similar to the S-LRP onset and the RT, with an earlier onset for stimulus matches than for the two mismatch types. That is, motor preparation started earlier in those cases with fast response selection. The expectation condition, however, did not affect motor preparation as measured by the LRP-R.

Response matches did not differ from complete mismatches in behavioral performance. Although response matches call for the same response as indicated by the cue or prediction, we did not find any benefit compared to complete mismatches. This finding suggests that response preparation depends on the imperative stimulus. Similarly, the N2 and P3 amplitude did not differ between response matches and mismatches whereas response matches differed significantly from stimulus matches in N2 and P3 amplitude measures. The facilitation of stimulus matches is reflected in the S-LRP onset and can, therefore, be attributed to perceptual and/or central parts of the preparation process. There was no difference between response matches and complete mismatches in the S-LRP and the LRP-R onset was similarly late for response match and mismatch. This is partly in line with what the theory of event coding (TEC; Hommel, 2009) would predict. Event codes are abstract codes encompassing features of perceived stimuli and (to be) produced actions. According to TEC, stimulus and response features are integrated into one event code. Event codes might be formed and retrieved both during prediction/cue processing and when the stimulus is presented and responded to (compare e.g., Wenke et al., 2007). Connecting and disconnecting features in an event code takes processing time. Thus, if we assume that explicit expectation provides some form of "preparative" event code, response matches, and complete mismatches should take longer than stimulus matches, in which all links set up by the expectation can be kept. This prediction is met by our data. However, TEC further predicts that complete mismatches are faster than response matches because a new event code is formed instead of disconnecting old and connecting new features as in the case of a response match (in a response match trial the predicted response has to be kept, but in combination with another stimulus). This prediction is not met because complete mismatches behaviorally do not differ significantly from response matches, and, in tendency, are rather slower than response matches.

Overall, S-LRP results mostly reflected behavioral performance. However, with self-generated predictions, both stimulus and response matches lead to an initial rise in the S-LRP, indicating an activation of the corresponding response. In the later course a faster rise for stimulus matches results in the S-LRP passing the onset threshold (defined at 50% of the peak amplitude) much earlier, while response matches do not pass this threshold before mismatches. This pattern suggests a preactivation of the correct response that was then inhibited due to the reevaluation after a different stimulus was shown. Presumably, inhibition seems to commence in response matches as soon as the mismatch between expected and presented stimulus is detected. This is interesting with regard to the role of stimuli in goal-directed action that Kunde et al. (2007) offer. They suggest that actions are generally goal-oriented and stimuli primarily serve to disambiguate between two variants: (1) a specific effect can be expected to follow an action in the current context, or (2) a goal is likely unattainable in the current context. Even simple actions such as button presses or operations of switches can have different effects depending on context factors. Presumably, the early S-LRP in response matches is indicating that action preparation, turning the expectation into an action goal, is no longer fostered (or even inhibited) once the stimulus signals a mismatch with the expectation.

DIFFERENTIATING TYPES OF EXPECTATION

We suggest that it is necessary to differentiate between self-generated and cue-induced expectations. This might be informative for research proposing similar distinctions with respect to other aspects of action control. For instance, in research on effect-based action control the role of action mode (free choice vs. stimulus-driven) in the acquisition (e.g., Herwig et al., 2007; Herwig and Waszak, 2012; Janczyk et al., 2012) or application (Pfister et al., 2011; Gaschler and Nattkemper, submitted) of action effect associations is under current debate. We suggest that effect anticipation might have an especially strong impact on action control if it is based on expectations about effects that stem from goals of the actor rather than being directly caused by current external stimulation. Expectations that are generated internally by integrating goals and past external stimulation might be represented more strongly as compared to cue-induced expectations, as the former need to be shielded against competing external stimulation (compare e.g., Dreisbach and Haider, 2008). When relying on cues that are present on each trial, a strong representation is not established as it is not necessary (compare e.g., Ballard et al., 1995).

We explain our results by a difference between self-generated and cue-induced expectations. A reviewer suggested an alternative account according to which the response time and ERP differences might be based on just one kind of expectation that plays out differently in these two experimental conditions. For instance, one could assume that the participant's expectation is in most cases validly reflected in the prediction condition. Thus, in most trials the participant would be expecting exactly what she or he verbally indicates. In contrast, a randomly presented cue might mirror the expectation on just some of the trials. While the cue suggests the expectation of a specific stimulus, the participant might not always follow this suggestion and often expect a different stimulus instead. By this account, expectation effects in the cueing condition might be as strong as in the prediction condition for the subset of trials in which participants expect what the cue suggests. It would be even conceivable that in this subset of trials of the cueing condition expectation effects might be stronger than those of the prediction condition, as potentially cues and internally generated predictions could be combined. However, as there is possibly a substantial proportion of trials in which participants do not follow the cue, one could expect that effects are on average smaller in the cueing condition as compared to the prediction condition. Though our experiment was not designed to test this alternative account, we analyzed reaction time data to evaluate this idea. According to the above view there should be no (or even a reversed) difference between the cueing and the prediction condition in the subset of trials in which there was likely a match between cue and internally generated expectation. This should be the case for the fastest 10% of match trials in the cueing condition. Percentile analyses did not support this conjecture. The 10% fastest match trials in the cue condition were *slower* than the 10% fastest match trials in the prediction condition [$\Delta = 27.39$ ms; $t(17) = 2.77$, $p = 0.013$].

A second possibility to address this concern is to scrutinize the influence of stimulus lag on the match effect in the cue condition. A typical fallacy often underlying predictions is the tendency to increasingly expect a stimulus alternation after longer runs of repetitions, also known as the "gambler's fallacy" (Ayton and Fischer, 2004). If a cue-independent internally generated expectation is effective in the cueing condition, a stimulus should be increasingly expected the longer it has not been presented. Indeed, in our sample the mean prediction probability for a stimulus increased from 16% when it had been presented two trials before to 30% when the last presentation was five or more trials back. The probability to predict a first-order repetition was on average 25%. All contrasts between the prediction probabilities for a stimulus presented at lag 1 (repetition prediction) to lag 5 or more were statistically significant. So, the predictions of our participants seem to reflect a mixture of a "gambler's fallacy"-like alternation bias and a first-order repetition bias. Therefore, if the cue matches a stimulus that has not been presented for several trials, the likelihood for the cue matching the "real" expectation should be highest. Consequently, one would expect the largest match effect at the longest lag of trials. We reanalyzed RTs of stimulus match and complete mismatch trials (there were not enough data points in some cells for response matches) of the cue condition. We found an effect for match, $F(1, 17) = 38.75$, $p < 0.001$, $\eta_p^2 = 0.70$, with no differences between lags [interaction match × lag: $F(1, 17) = 1.43$, $p = 0.232$], while RTs generally increase over lags for match and mismatch trials (main effect of lag: $F(1, 17) = 8.88$, $p < 0.001$, $\eta_p^2 = 0.34$). In the case of a stimulus repetition the effect tended to be larger (41 ms), rather than smaller, compared to the effect at longer lags (22, 20, 25, and 20 ms, for lags 2, 3, 4, and more than 4, respectively). Currently, our data does not support the view that there is only one kind of expectation effective in both the cueing and prediction condition. Rather, the data suggests that expectation in the cueing condition is different from expectation in the prediction condition. As these *post hoc* analyses provide only preliminary arguments, the task to disentangle the interactions between internal and externally motivated expectation remains open to future research.

One can further argue that self-generated expectations can not be controlled experimentally to the same extent as cue-induced expectations. Yet we suggest that it is warranted to (also) use self-generated expectations for studying effects of expectation on goal-directed action. Research on task switching has witnessed a similar case where presumably external validity and experimental control have to be balanced. It could be shown that a voluntarily initiated task choice results in different behavioral effects as compared with the situation where the task set to be implemented is triggered by a cue: voluntary task switches lead to much smaller task switching costs than cued task switches (Arrington and Logan, 2005). Thus, not only in the preparation of simple actions but also at the superordinate level of task sets there are differences between self-initiated and externally triggered processes. Participants in the Arrington and Logan (2005) study were instructed to choose freely between two possible tasks (with about the same frequency and in an approximately random manner). Thus, they decided on a task to prepare for, or, to put it differently, they expected to execute the chosen task as soon as the stimulus appeared (cf. Kunde et al., 2007). Accordingly, after being cued, they prepared to execute the task given by the cue. This situation, therefore, is similar to the approach of the current study: performance differences are observed as a consequence of preparation determined by internal or external sources. However, it is not clear if the differences are based on qualitative differences between internally or externally initiated task preparation processes, or if it may already be the source of expectation generation (i.e., before any preparation starts) that affects the consecutive task processes.

The findings from voluntary task switching suggest that the two paths to action might already differ prior to stimulus presentation. Accordingly, expectations prior to stimulus presentation may vary and differently affect action preparation depending on whether they are cue-induced or self-generated. Moreover, the idea of stimulus-based and intention-based action control modes (e.g., Herwig et al., 2007) can be mapped to what is (not) necessary to build-up explicit stimulus expectations in cueing vs. self-generation: while cues can potentially act as rather automatic triggers for a specific expectation (e.g., Bargh and Chartrand, 1999), the requirement to generate predictions can only be fulfilled intentionally (compare e.g., Jahanshahi et al., 2006). As expectations are a part of the action it seems plausible that participants are more likely to be in an intention-based mode if they generate expectations themselves. Moreover, expected or unexpected stimuli in this context represent feedback (i.e., action effects) to the expectations, and the contingency between expectations and stimuli should impact performance to a larger extent if it is acquired in an intention-based mode (Pfister et al., 2011). This could explain the performance differences between prediction and cue trials in Acosta's (1982) and our study.

The difference between self-generated and cue-induced expectations and their role in action control requires further study. We have demonstrated that these types of expectation differ in a situation in which both are explicitly verbalized using the same words as output (naming the predicted differentiating stimulus feature vs. reading the cue word of this feature). A study trying to generalize the different expectation effects beyond this specific verbal task seems promising. Furthermore, it is necessary to test accounts of how and why self-generated and cue-induced expectations differ. As of yet, it is not clear whether the two types of expectation differ qualitatively or quantitatively. Self-generated expectations might either show stronger and/or qualitatively different effects on action preparation and performance. For instance, one could argue that a difference in the results might simply be due to an artifact in the methods used to induce the two types of expectation. On the one hand, reading aloud the cues does not enforce deep processing. In an implicit sequence learning study with a repeating sequence of to be read words, Hartman et al. (1989) demonstrated a surprising lack of explicit and even implicit learning. Generating the predictions, on the other hand, might enforce deeper processing for various reasons. For instance, participants were instructed that expectations should not be the same all the time. The experimenter was present outside the EEG booth coding the expectations online. Thus, the self-generated expectations were constrained such that they should be somewhat variable from trial-to-trial, avoiding perseverance and obvious patterns. This likely enforced that participants allocated a substantial part of their resources to the expectations in the prediction version of the task (compare e.g., Rapoport and Budescu, 1997).

Looking for functional differences between different types of expectation, Bubic et al. (2009, 2010) employed EEG and fMRI to investigate involved brain structures and processes. Violations of sequential regularities were accompanied by increased activity in premotor and cerebellar components of the "sequencing network," presumably reflecting a mismatch between expectations generated by a forward model (cf. Wolpert and Ghahramani, 2000) and the observed stimuli – and an adjustment of the model. In addition, lateral prefrontal areas were engaged when a sequence violation required a boost in cognitive control. Stimuli deviating from a context of standard stimuli by a certain feature (as in an oddball paradigm), on the other hand, triggered responses in bilateral posterior temporal and parietal areas, reflecting increased attention and perceptual processing (Bubic et al., 2009). Interestingly, they also report differences in both the N2 and P3 components between their expectation conditions. While the N2 exhibited a shorter latency for sequential deviants compared to feature deviants, the P3 peaked later in the first condition and had a smaller amplitude. In line with the activation pattern reported in their imaging study, both components had a more posterior distribution for feature deviants. Additionally, they identified an enhanced N1 component for feature deviants, suggesting an early sensory registration of the irregularity (Bubic et al., 2010). The authors take these findings as indication for distinct functional networks involved in the processing of different types of expectation. It remains an interesting question whether similar functional differences also apply to the distinction between self-generated and externally cued expectation studied here.

CONCLUSION

Self-generated expectations differ from cue-induced expectations on a range of cognitive processing stages and result in stronger behavioral effects. Response time benefits for expected stimuli are much larger when expectations are self-generated as compared to externally cued. Higher amplitudes in both the N2 and P3 components for violations of self-generated expectations indicate increased premotoric preparation compared to cue-induced expectations. This goes along with a missing benefit for stimuli matching the expected response only and is mirrored in the LRP. Underlying cognitive or neuronal functional differences between these types of expectation remain a subject for future studies.

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Appendix C

Study III

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The impact of self-generated vs. cue-induced expectations on preparation for task sets

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Abstract

Alternating between different tasks typically results in impaired performance compared to repeating the same task. The ubiquity of task switch costs has led to the assumption that people are generally unable to fully prepare for a change in tasks, even when it is to be expected. To assess the influence of expectations on task switching performance, we had participants self-generating verbal task predictions. In a second condition, participants had to read aloud word-cues indicating the upcoming task. Performance effects were related to expectation: a correctly predicted task switch entailed no switch costs (50% switch probability) or even reversed switch costs (80% switch probability). Self-generated expectations enabled task-set preparation to a higher degree than cue-induced expectations. When relying on their subjective expectation, people are able to overcome the commonly found reluctance to switch tasks and fully prepare for an upcoming change. To understand task-switching performance, it’s not enough to look at the current (or recent) stimulation. It is important to account for internal subjective expectation as well.
Keywords: Task switching, switch-unspecific preparation, proactive processes, self-generated expectation, cue-induced expectation, verbal mediation

Introduction

In the early evening of May 8, 2009, 24-year-old Aiden Quinn was driving his Green Line trolley through downtown Boston, exchanging text messages with his girlfriend at the same time. While looking down on his cellphone, “he noticed red lights, looked up, attempted to apply the brake, and it was too late,” as the chief of the Boston area’s transit authority, Daniel Grabauskas, told the press later (http://www.nytimes.com/2009/05/10/us/10boston.html). Quinn’s train crashed into another trolley that was stopped at a red signal, injuring 49 passengers. This example is just one of countless accidents caused by people trying to focus on more than one task at a time.

Psychologists have known for long that we are notoriously bad at multitasking, or switching from one task to another, taking more time in doing so and making more errors compared to sticking with just one task (e.g., Allport, Styles, & Hsieh, 1994; Jersild, 1927; see Kiesel et al., 2010, for a recent review). While such “switch costs” may not carry as severe consequences in the lab as, say, on the road, task-switching experiments have provided many insights into this phenomenon. Impaired performance for task alternations has been reported even when tasks were presented in predictable sequences (e.g., Rogers & Monsell, 1995), when they were validly cued (e.g., Meiran, 1996), or when participants were able to choose between tasks voluntarily (e.g., Arrington & Logan, 2004). This has led researchers to suggest a “structural inability to fully prepare for a task switch” (Kiesel et al., 2010, p. 855).

The idea that we cannot (fully) prepare for an expected change (cf. Duthoo et al., 2012) seems to contradict the notion of the “proactive brain” (Bar, 2009a) that has gained a lot of support recently (see Bar, 2011, for a recent collection). The above cited paradigms were constructed in ways that could enable participants to form reliable expectations about the upcoming task. In single-task paradigms, expectations regarding the upcoming trial have been shown to drive preparation, boosting performance (e.g., Umbach et al., 2012). If the generation of predictions is one of the "universal principles that can explain the majority of [the brains] operation" (Bar, 2009b, p. 1181), the apparent lack of preparation for expected switches calls for further investigation. The aim of this study is to analyze the role of expectation in task switching.

The consistent finding of performance differences between task repetitions and alternations has led to a variety of theoretical explanations that can be grouped into two opposing views: a reactive and a proactive account of task switching. According to the *reactive* account, control adjustments necessary to overcome a conflict between alternating tasks are implemented in response to a target (cf. Botvinick et al., 2001). Switch costs are often thought to stem from the involvement of additional processes in a task switch (such as "task-set reconfiguration") that are not required in task repetitions. These switch-specific processes are further divided into two stages: the first can be completed in advance, allowing for a partial preparation benefit for expected switches, while the second stage relies on the presentation of the stimulus. Such two-stage models therefore explain "residual switch costs" with the necessarily incomplete preparation (e.g., Roger & Monsell, 1995). Apart from influences of cognitive control, benefits of repetitions over switches could be explained by passive carry-over effects: in terms of priming effects of the previous task in case of repetitions, or in terms of interference from the previous task in case of switches. According to a purely reactive view, expectations regarding the sequence of tasks therefore should play no role for task switching. Switching costs would be determined mainly by the relation of the current task to the task in the preceding trial.

A *proactive* account, however, would assume anticipatory control adjustments, or preparation based on expectation (see Umbach et al., 2012). Support for a proactive view on task switching stems from a wide range of studies revealing reduced switch costs if the task is known in advance and there is at least some time to prepare. This effect has been replicated with various tasks and experimental designs (cf. Kiesel et al., 2010) and proven to be present independently of carry-over effects from the previous task (e.g. Meiran, 1996). A reduction in switch costs with a longer preparatory interval was also found if the participants chose themselves when to repeat and when to switch tasks (Arrington & Logan, 2004). This evidence demonstrates than we can do at least a part of the switch before the target if we have the possibility to anticipate the upcoming task, either by being informed externally or by choosing it ourselves. As performance improvements by valid precueing are present in repetition trials as well (e.g. Monsell & Mizon, 2006), some studies failed to find a reduction in switch costs because the response times shortened to the same extent for task repetition and task switch trials (e.g. Altmann, 2004). Similarly, performance on task switch as well as on repetition trials has been shown to be better if the sequence of tasks is fixed (i.e., predictable) as compared to if it is randomly cued, resulting in similar costs for a task switch in both conditions (Koch, 2005). Advance preparation, thus, appears to be not switch specific but to relate to the upcoming task, regardless of switch or repetition.

There is some evidence in the literature hinting to a role of subjective task expectation in the emergence and extent of switch costs. Mayr (2006) found smaller costs in a four-cues-two-tasks-paradigm if the proportion of task switches was high. He concluded that participants under conditions of high switch probability prepare for a switch rather than for a repetition (see also Dreisbach & Haider, 2006). Higher costs for a cue switch in combination with a task repetition under these circumstances support this conclusion. Expectation effects were considered more directly in a study of Dreisbach, Haider and Kluwe (2002). They suggested a mixture of an activation advantage of the repeated task (automatic carry-over effects or task-set adaptation) and preparation according to (cued) task expectations. Using cues that announced one of four tasks with a certain probability (from .25 to 1) they could show that performance for repetition as well as for switch trials was better with higher probabilities (i.e., more valid precues). A constant switch cost for tasks cued with the same probability suggests that the activation advantage of a repeated task set influences task switching performance independently of expectation. Clearly, preparation effects in cueing paradigms could be caused by reactive processes in response to the cue. Cue switching costs (e.g., Mayr & Kliegl, 2003; Logan & Bundesen, 2003) are a stable finding that supports this view. Probably, cueing effects are a mixture of priming and expectation effects and, thus, somewhat problematic if one wants to investigate the role of expectation on preparation for a task.

A recent study by Duthoo and colleagues (2012) probed the proactive account by looking at the impact of self-generated predictions in task switching. In a typical magnitude/parity task-switching paradigm, they asked participants to predict the upcoming task on every trial. Between subjects, the probability of task alternations varied from 30% over 50% to 70%. They found the highest performance following correct repetition predictions, while a false repetition prediction (that was actually followed by a task alternation) impeded performance the most. There were no performance differences between task repetitions and alternations following an alternation prediction. The authors therefore concluded that switch costs only arise in conjunction with repetition predictions. This finding is in line with the repetition benefit view of task switching. Importantly, participants in their study heavily overestimated the proportion of repetitions, indicating a repetition bias (in all three conditions). While also partly in line with a proactive account of task switching, the study by Duthoo and colleagues (2012) leaves open the question "to what extent our brain can also prepare for expected changes" (p. 8). In their study, preparation for alternations was always incomplete, leaving a residual cost (correctly predicted repetitions were faster than correctly predicted alternations). A "truly" proactive account would assume similar preparation for repetitions and alternations. If people expect a change, and expectation leads to preparation, they should be able to prepare for that change.

A potential methodological issue in the Duthoo et al. (2012) study lies in the use of manual predictions and responses with the same hand. This could have resulted in hand priming and might therefore have artefactually increased the reported repetition benefit. For example, a participant presses a key with his left hand to indicate that he expects the magnitude task on a given trial. If the task following that prediction is indeed the magnitude task, the participant has to use his left hand again to respond to it. As he has just used that hand before, the response might come faster as if he had to use his other hand to respond to the parity task. Therefore, task switch performance might have additionally suffered from the necessary switch in hands. This potential confound can be eliminated by the use of verbal predictions in place of manual ones. The verbalization of the to-be-performed task has been shown to improve task-switching performance, while pronouncing task-irrelevant words impaired performance (Goschke, 2000). This is in line with the idea that inner speech facilitates action control (Luria, 1969). In a single-task paradigm, verbalized expectations have been shown to exert a larger influence on action preparation compared to non-verbalized internal expectations or external cues (Umbach et al., 2012).

As we were interested specifically in proactive influences on task switching performance, we also included a comparison between self-generated and exogenously triggered expectations in their impact on subsequent processing. Recently, a study from our lab (Kemper et al., 2012) demonstrated that self-generated expectations differ from cue-induced expectations on a range of processing stages and result in stronger behavioral effects (Kemper et al., 2012). Increased premotoric preparation for self-generated predictions was indicated by higher amplitudes in the N2 and P3 components. LRP results were also in line with a premotoric locus of the prediction effect. Often experimenters resort to cueing procedures to induce expectations, as these are seemingly easier to control. However, internally generating expectations themselves might not only come closer to what people do outside the laboratory, but also involve different cognitive mechanisms and result in different behavioral outcomes. As this is true for simple stimulus expectations (Kemper et al., 2012), it's informative to look at the same comparison in relation to task expectations.

In the current study, we wanted to challenge the assumption that people cannot fully prepare for an expected task alternation (cf. Duthoo et al., 2012). In the spirit of the "proactive brain", we hypothesize that (1) people are able to prepare for a correctly predicted task alternation if the situation makes it reasonable for them to strongly rely on their predictions (i.e., when their chances of scoring a correct prediction are above average). Therefore, we also included a condition with 80% task alternations, increasing the likelihood of scoring a correct alternation prediction. In contrast to the conclusion by Duthoo and colleagues (2012), we assume the prediction effect in task switching does not rely exclusively on repetition predictions. Also, we wanted to see whether this effect also hold for verbal (instead of manual) predictions. This would rule out alternative explanations of motoric priming. In line with the verbal mediation effects on task-switching performance cited above, we hypothesize that (2) verbalizing tasks will improve performance and reduce switch costs when the prediction is correct - and impair performance in case of an incorrect prediction. Finally, we wanted to check whether the difference between self-generated and cue-induced expectations found in single-task paradigms also holds for a task-switching paradigm. We hypothesize that (3) the effect of self-generated predictions on task-switching performance is stronger than that of cue-induced expectations.

Method

Participants

42 participants (26 women, aged 19 to 35 years) took part in individual sessions lasting approximately 60 minutes, receiving either partial course credit (for psychology students) or a monetary compensation of 8 euros. All participants had normal or corrected-to-normal vision and were native German speakers. Two participants were left-handed.

Apparatus and stimuli

The experiment was presented on a Windows computer with a 17-inch CRT monitor and controlled by a MATLAB script with the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). Stimuli were colored circles presented in two shades of blue (RGB values 0, 0, 255 and 30, 144, 255) and two sizes (1.3 and 2.6 cm, corresponding to visual angles of about 1.5 and 3 degrees at a viewing distance of approximately 50 cm) on a light grey background above or below a black horizontal midline. Verbal responses (cues, predictions) were recorded using a headset microphone to obtain voice onset times; self-generated predictions were simultaneously coded by the experimenter sitting next to the participant on a separate computer. Target responses were made on a standard Windows keyboard using the index and middle fingers of both hands. Acoustic error feedback was given via headphones after erroneous responses.

Design and procedure

Participants were either confronted with an equal amount of task repetitions and alternations (50%, *medium switch probability*) or with an increased proportion of alternations (80%, *high switch probability*) in a between-subjects design. Each experimental session consisted of two parts, a cue-induced (*cue condition*) and a self-generated expectation variant (*prediction condition*), establishing expectation source as a within-subjects factor. The order of these two parts was counterbalanced across participants. On all trials, targets were circles that had to be categorized by either color shade (light/dark) or size (big/small, see details above). Targets were presented above or below a horizontal midline, indicating which task to perform in the current trial (color/size). All target combinations had the same presentation frequency with a randomized order of appearance. Also, the two tasks were presented randomly at equal probabilities.

At the beginning of each trial participants had to verbalize an expectation regarding the upcoming task. They either read aloud the word “Farbe” or “Größe” (German for color and size, respectively) displayed on the screen in the cue condition, or they self-generated one of these words in response to a prompt (question mark) in the prediction condition. (Both cue/prediction words were two-syllable nouns, reducing lexical variability.) Cues had the same frequency as tasks and were independently randomized, therefore correctly indicating the upcoming task on half the trials in the medium switch probability condition (50% validity). In the high switch probability condition, cues predicted a switch on 80% of all trials (mirroring the actual switch probability), leading to a validity of 68%. It was explained in the instruction that cue words hinted at the upcoming task and could be either valid or not. In the prediction condition, participants were instructed to guess the upcoming task themselves. These predictions were then manually coded by the experimenter, who was present in the lab room throughout.

The cue or prediction prompt (and the subsequent verbalization) was followed after 2,500 ms by the target stimulus (described above). Participants had to respond by pressing one of two buttons with either the index or the middle finger of the hand corresponding to the current task. Left and right hand were mapped to the color and size task, and this response mapping was counterbalanced across participants. The next trial started 500 ms after a button press was registered.

Two training blocks of 10 trials each preceded four regular blocks of 88 (medium switch probability) or 80 trials (high switch probability) in each expectation condition (cue/prediction). Successive presentation of task repetitions and switches was controlled to resemble a pattern expected by chance, following a method described by Jiménez & Méndez (2013; see also Perruchet, Cleeremans, & Destrebecqz, 2006; Nicks, 1959). For each block and task we included two runs of four trials, four runs of three trials, eight runs of two trials, and eight runs of one trial, adding up to 88 trials in the medium switch probability condition. In the high switch probability condition we included two runs of three trials, four runs of two trials, and 26 runs of one trial for each task and block, adding up to 80 trials. These runs were then randomly arranged for each block and participant, with the constraint that a given run could not be followed by another run of the same task.

Results

One participant was excluded from the analysis because of a technical error with data collection. Another participant was excluded for predicting the same task on every trial throughout the experiment. Three more participants were excluded for producing too many errors (more than 2 SD above the mean of all participants). The analysis was carried out on the remaining 37 participants (18 in the medium switch probability and 19 in the high switch probability condition). We did not include the first trial of each block and removed error trials from the RT analysis (6%). RT outliers (± 2.5 SD, calculated separately per group, subject, condition, and task) were also removed (2.3%), leaving 90.5% of the complete data for the analysis.

A mixed-design ANOVA on RT with the between-subjects factor Switch Probability (medium vs. high) and the within-subjects factors Condition (cue vs. prediction), Task (color vs. size) and Sequence (repetition vs. alternation) revealed only a main effect of Task, $F(1, 35) = 37.65$, $p < .001$, $\eta_p^2 = .52$, reflecting faster size than color judgements (711 vs. 802 ms), and a significant interaction between Sequence and Switch Probability, $F(1, 35) = 27.77$, $p < .001$, $\eta_p^2 = .44$, implying that switch costs were affected by the probability manipulation. There were no main effects for Switch Probability, F(1, 35) = 1.28, ns, or Condition, F(1, 35) < 1, ns, and, importantly, no main effect for Sequence, F(1, 35) = 2.62, $p = .115$, indicating that there were *no* overall switch costs, at least in this analysis. No other interactions turned out significant. A follow-up paired samples *t*-test revealed significant task switching costs (79 ms) for the medium switch probability group, $t(17) = 7.14$, $p < .001$, and *reversed* switching costs (-41 ms) for high switch probability group, $t(18) = -2.12$, $p = .048$ (multiple comparison correction according to the Holm-Bonferroni method; Holm, 1979).

Looking into the prediction patterns, we found that in both groups the color task was predicted in 51% of all trials on average (SD = 3%), indicating that participants followed the instructions, correctly reproduced the equal task probabilities and were not biased towards one task. In the high switch probability group there were more alternation predictions (60%) than in the medium switch probability group (45%), $t(35) = 2.79$, $p = .008$. Participants therefore adapted their predictions to the given switch probabilities. While there was no repetition bias in the medium switch probability group (55% predicted vs. 50% actual repetitions), $t(17) = 1.53$, $p = .146$, participants in the high switch probability group manifested a repetition bias (40% predicted vs. 20% actual repetitions), $t(18) = 4.69$, $p < .001$. The overall validity of predictions was at 51% correct in the medium switch probability group and 57% in the high switch probability group, while cue validity varied from 46% in the medium to 67% in the high switch probability group. Mean verbalization latency in both groups was at 354 ms for predictions (SD = 244 ms) and 335 ms for cues (SD = 152 ms).

The effects of predictions (and cues) on task-switching performance were tested in a mixed-design ANOVA on RT with the between-subjects factor Switch Probability and the within-subjects factors Condition, Sequence and Expectation (repetition vs. alternation). In this analysis (see Figure 1), the main effect of Sequence became significant, $F(1, 35) = 24.84$, $p < .001$, $\eta_p^2 = .42$, hinting at the importance of taking expectations into account when looking at task-switching costs. This is underlined by the main effect of Expectation, $F(1, 35) = 7.38$, $p = .010$, $\eta_p^2 = .17$. There were again no differences between groups (Switch Probability, $F(1, 35) = 1.4$, ns) and sources of expectation (Condition, $F(1, 35) < 1$, ns). As in the above analysis, the interaction between Sequence and Switch Probability, $F(1, 35) = 26.54$, $p < .001$, $\eta_p^2 = .43$, reflected the difference in switch costs between the probability groups. A significant interaction between Sequence and Expectation, $F(1, 35) = 73.45$, $p < .001$, $\eta_p^2 = .68$, confirmed the influence of expectations on task-switching costs. Finally, this effect of expectation on switch costs differed between predictions and cues, as manifested in a three-way interaction between Condition,Sequence and Expectation, $F(1, 35) = 9.57$, $p = .004$, $\eta_p^2 = .22$. No other interactions became significant (all $F < 1$). A follow-up paired samples *t*-test revealed that in the medium switch probability group, switch costs were only present following repetition predictions or cues (144 ms), $t(17) = 9.32$, $p < .001$, but disappeared following alternation predictions or cues (1 ms), $t(17) < 1$, ns. In the high switch probability group, switch costs following repetition predictions or cues (78 ms), $t(18) = 7.00$, $p < .001$, were reversed following alternation predictions ot cues (-83 ms), $t(18) = -3.77$, $p = .001$. Also, there were no residual switch costs in the high switch probability group (correctly predicted alternations vs. correctly predicted repetitions), $t(18) < 1$, ns.

An analysis of the error rates in a mixed-design ANOVA with the between-subjects factor Switch Probability and the within-subjects factors Condition, Sequence and Expectation revealed main effects for Switch Probability, $F(1, 35) = 4.89$, $p = .034$, and Condition, $F(1, 35) = 4.54$, $p = .040$, as well as two-way interaction between Sequence and Expectation, $F(1, 35) = 11.56$, $p = .002$, and a four-way interaction Probability x Condition x Sequence x Expectation, $F(1, 35) = 4.32$, $p = .045$. No other effects became significant.

Discussion

The aim of this study was to analyze the role of expectations in preparing for repeating or alternating tasks. In a task-switching paradigm, participants had to either judge the size or color of circles, with the current task indicated by the screen position of the circle. Task expectation was either induced by explicit word cues (that had to be read aloud) or self-generated by participants through verbal predictions. One group of participants was confronted with an equal amount of task repetitions and alternations (medium switch probability), while for another group tasks alternated on 80% of trials (high switch probability). Switch costs were affected by the probability manipulation, with impaired performance on alternation trials in the medium switch probability group and *improved* performance (switch benefit) in the high switch probability group. This effect was apparently mediated by expectation: following an alternation expectation, there were no switch costs in the medium switch probability group, and reversed switch costs in the high switch probability group. In line with this reasoning, participants adapted their predictions to the given switch probabilities, with more alternation predictions in the high switch probability group. There were no residual switch costs (between correctly predicted alternations and correctly predicted repetitions) in the high switch probability group. The expectation effect on performance was stronger for predictions than for cues.

Proactive task switching

Our hypothesis that (1) people are able to prepare for a correctly predicted task alternation was confirmed. With correct predictions, switch costs were reduced or even reversed (in the high switch probability group). We could also show that this effect does not rely exclusively on repetition predictions. As there was no difference between correctly predicted alternations and correctly predicted repetitions in the high switch probability group, our results indicate that people are able to prepare for a correctly predicted task alternation if the situation makes it reasonable for them to strongly rely on their predictions. The lack of residual switch costs in our study makes it unnecessary to assume any additional switch-specific process. This is consistent with the repetition-benefit view, assuming similar preparatory processes in switch and repeat trials. This repetition benefit can at least partly be traced back to expectation-based preparatory processes, as participants were overestimating the amount of repetitions in the high switch probability group. The lack of such a repetition bias in the medium switch probability group, however, points to the additional influence of automatic carry-over effects from the previous trial. More important yet is the finding of similar performance for correctly predicted alternations and repetitions (in the high switch probability group). This speaks in favor of a truly proactive account of task-switching.

Recently, Duthoo and colleagues (2012) also looked at the impact of self-generated predictions on task-switching performance. While replicating their main finding that task preparation is influenced by expectation, a few important differences emerge between their study and ours. While Duthoo and colleagues (2012) reported a consistent repetition bias across all switch probabilities ranging from 30% to 70%, participants in our study only overestimated the amount of repetitions in the high switch probability condition (80%), but not in the medium switch probability condition (50%). This divergent finding raises the questions whether (a) the repetition bias is as stable across procedures as Duthoo et al. (2012) assume, and whether (b) the repetition benefit found in most task-switching studies can be traced back to such a repetition bias, as the authors argue. In fact, people are prone to a variety of biases when judging the probability of events. As Ayton & Fischer (2004) have shown, such biases can arise from real-life experience and often lead to adaptive behavior. When observing a series of events where the outcome is determined by human performance (such as consecutive shots taken by a basketball player), people tend to assume a positive recency ("hot hand fallacy"). Events determined by chance (such as consecutive coin tosses), on the other hand, tend to invoke a negative recency expectation ("gambler's fallacy"). In a recent study from our lab (Umbach et al., 2012), we found that people are able to adapt their predictions fairly quickly to the actual probabilities experienced in a task. This kind of bevavioral adaptation has also been described as probability matching (e.g. Gaissmaier & Schooler, 2008). Taken together with the results of the current study, these findings suggest that there is no universal repetition bias in task predictions that can be obtained in all experimental procedures and conditions. The reasoning by Duthoo et al. (2012) that typical task-switching performance can largely be explained by this bias must therefore be questioned. In our medium switch probability condition, participants achieved a repetition benefit without displaying any repetition bias in their predictions. Besides subjective expectation, there might have been an additional influence of automatic carry-over effects from the previous trial, leading to the observed repetition benefit. The impact of subjective expectation might be particularly strong when people have learned to rely on it, as it was possible in the high switch probability condition. When prediction hit rate was at chance level (as in the medium switch probability condition), participants might have relied less on their subjective expectation and allowed for a stronger influence of automatic priming processes.

In the high switch probability group in our study, there were no performance differences between correctly predicted repetitions and correctly predicted alternations. We therefore did not find the residual switch costs reported by Dutoo et al. (2012). The expectation effect on task-switching performance reported here did not rely on repetition predictions only. Participants in our study were able to prepare for predicted alternations, too. This even resulted in reversed switch costs, with an expected task switch taking less time than an unexpected task repetition. Preparation and performance were clearly linked to subjective expectation. This suggests a strong influence of proactive processes in task-switching and contradicts the idea that we cannot fully prepare for a task switch (cf. Kiesel et al., 2010; Duthoo et al., 2012).

Switch-unspecific preparation

In contrast to the conclusion suggested by Duthoo et al. (2012) our results demonstrate that the expectation effect on task-switching performance does not rely exclusively on repetition predictions. Rather, people are able to prepare for a correctly predicted task alternation if the situation makes it reasonable for them to strongly rely on their predictions. This goes along with findings showing switch-unspecific preparation effects in task switching. These results correspond to other findings reported in the literature.

In a study by Dreisbach and colleagues (2002) expectancy for task repetitions and alternations was manipulated by probability cues. Participants had to perform one of four tasks on each trial. Prior to the task stimulus, a cue announced the probability for a task repetition or a switch to one of the other three tasks. Probability rates were 1.00, .75, .50, or .25. The authors found equal preparation effects for task repetitions and switches. Switch costs did not vary between probability conditions. These findings suggest that preparation is not switch-specific but rather an additive factor to the actual switching process. The authors argue that if expectations are not explicitly manipulated, participants might implicitly overestimate the number of task repetitions as these are easier to perform, leading to the commonly found disadvantage for switch trials. As the repetition advantage was not influenced by expectancy-driven preparation in their study, the results support the view of an automatic carry-over effect leading to a repetition benefit.

To further examine dynamic preparatory adjustments during task switching, Dreisbach and Haider (2006) conducted an experiment in which they manipulated task frequency as well as expectancy type. Participants had to perform either a magnitude or a parity judgment on a single digit, with the digit's color indicating which task to perform. Task frequency was manipulated between blocks (75% vs. 25% switches). The current frequency was either announced once before the block started (global expectancy condition) or repeatedly indicated before every trial (local expectancy condition). The authors found stronger overall preparation effects leading to reduced switch costs in high shift blocks compared to high repetition blocks. Furthermore, while RTs in the local expectancy condition were affected by task frequency, there were no RT differences between probable and improbable task shifts in the global expectancy condition. Also, no switch costs occurred in the 75% shift block in the local condition. These findings support the assumption of preparatory adjustments to current task demands. When faced with higher task demands such as frequent task shifting, participants put more effort in preparation, thereby reducing switch costs. These preparatory adjustments do not need explicit cues but can already be triggered by global probability information. However, local expectancy seems to facilitate backward inhibition of improbable repetitions more than global expectancy, extinguishing switch costs.

In an attempt to separate true task switch costs from mere cue switch costs in the cuing paradigm several studies were conducted using a 4:2 mapping between cues and tasks. Results, however, were contradictory, with some studies showing substantial task switch costs (e.g. Mayr & Kliegl, 2003) while others report none or only small task switch costs (e.g. Logan & Bundesen, 2003). Along with differences in the experimental procedures in terms of switch probability, these inconsistent results have led to an ongoing debate as to the existence and nature of true task switch costs, i.e. the difference in RTs between cue-switch and task-switch transitions.

On the one hand, the "task-level adaption" account suggests a probability-based adaption of task set configuration activities. According to this view, high task switch probability can reduce switch costs because subjects adapt to frequent switching and thus prepare more often for a task alternation than for a repetition. Possibly, they may also consider cue switches when deciding whether to prepare for a task switch or a task repetition. Thus, high task switch probability increases the conditional probability of a task switch given a cue switch, leading to a reduction of true task switch costs but an increase of cue switch costs.

On the other hand, the cue-priming account states that throughout the experiment subjects learn specific cue-cue transitions. Hence, reduced switch costs in case of a high task switch probability are not due to a general adaption to frequent switching. Rather, with high task switch probability those cue-cue transitions that go along with a task alternation appear more often, resulting in a priming advantage due to their frequency.

To distinguish between those two accounts, Mayr (2006) conducted a study in which he manipulated the probability of specific cue transitions. Results support the "task-level adaption" account. No significant differences between the two sets of switch-trial transitions could be found. Apparently, manipulating the probability of specific cue-cue transitions does not affect switch costs. Cue switch costs were larger for the high-probability group, while task switch costs were larger for the low-probability group, indicating that switch probability affects switch costs independently of specific cue transitions. Moreover, these findings hint at the importance of conditional task switch probabilities, which in turn influence expectations.

Taken together, these findings hint at the influence of subjective task expectations when switching back and forth between different tasks. The effects of expectation remain visible when controlling for effects of task repetition or (passive) priming. Expectation is switch-unspecific in that it enables preparation not only for repetitions (cf. Duthoo et al., 2012), but also for task alternations.

Verbal mediation in task switching

We confirmed the hypothesis that (2) verbalizing tasks will improve performance and reduce switch costs. Instead of manual predictions (cf. Duthoo et al., 2012), we made use of verbalized predictions. As pointed out above, verbal mediation has been shown to benefit task switching performance. Verbalizing task relevant words enables preparation for that task. At the same time, we eliminated a possible confound in the Duthoo et al. (2012) study. As participants in their study used the same hand to indicate their prediction and to respond to that task, they might have profited from hand priming in case of a correct prediction. The reported prediction benefit therefore might have been at least in part due to automatic motoric priming effects. As we found a clear advantage for correctly predicted tasks without manual predictions, we can rule out this possible confound. The effect of self-generated predictions on task-switching performance reported in the current study and also by Duthoo et al. (2012) cannot be explained by automatic motor priming effects.

Our finding that the verbalization of task descriptions can improve performance and reduce switch costs goes along with findings on verbal mediation in task switching. For example, a study by Miyake and colleagues (2004) looked at the role of inner speech in task switching. Participants in their study were asked to either name the upcoming task as triggered by a cue or perform an articulatory suppression (by pronouncing unrelated words). Cues were either complete task names or their initial letters only. Results showed no reduction in switch costs for the word cue condition compared to the articulatory suppression at a long cue-stimulus interval (1,200 ms). However, in the letter cue condition, articulatory suppression led to significantly larger switch cost.

These findings suggest that the negative impact of articulatory suppression on switch cost depends on the cue type. With explicit word cues that automatically activate a representation of the task goal, inner speech as retrieval aid might not be necessary, making concurrent articulatory suppression less harmful. With less explicit cues, such as the initial letter of the task name, inner speech seems to become much more important for translating those cues into task names and activating the correct task set, leading to less efficient mental set shifting when interfered by concurrent irrelevant articulation.

A related finding comes from Logan and Schneider (2006), who found congruency effects between task cues and stimuli only with transparent (word) cues but not with nontransparent (letter) cues. Similar to Myiake et al. (2004) the authors argue that transparent word cues (naming the upcoming task) facilitate task set retrieval and work as mediators for the appropriate response.

Kirkham, Breeze & Marí-Beffa (2012) investigated potential benefits of task-relevant verbalizations in an alternating runs paradigm. Participants in their study were asked to read aloud a descriptive word cue indicating the upcoming task (shape or color distinction on bivalent stimuli). This procedure enabled faster responses compared to a silent reading and an articulatory suppression condition. While reading aloud reduced mixing costs (calculated as the difference between trials in a pure repeat block and repeat trials in a mixed block of trials), there was no influence on switch costs (difference between repeat and switch trials in a mixed block). In a second experiment, the authors found that presenting auditory cues (in addition to visual cues) had similar effects compared to reading aloud the verbal cues; both resulted in reduced response times as well as reduced mixing costs and switch costs (compared to silent reading). These findings demonstrate that task-relevant verbalizations clearly benefit preparation processes. Even when participants are not required to speak aloud, they might use subvocal strategies to achieve similar results. The participants in the Kirkham et al. (2012) study all indicated in a post-experiment questionnaire that they had engaged in inner speech during the silent reading condition. The additional articulatory and auditory processes in the reading aloud condition provided an additional boost. As there was mainly an impact on mixing costs and not on switching costs, the authors argue that verbalizations benefit the preparation and speedy execution of repetition trials, but not switch trials.

The word-cue conditions used by Miyake et al. (2004) and Kirkham et al. (2012) can be compared to our cueing condition. Pronouncing a correct cue resulted in faster response times compared to a false cue, but this effect was much larger for self-generated predictions (with no differences in the verbalization procedure). Presumably, inner speech is involved to a greater degree in the generation of predictions than in reading aloud task cues. The switch-unspecific preparation effects discussed before cannot be explained solely by our verbalization procedure, but rather stem from the requirement to engage in proactive task prediction.

Self-generated predictions

Relating to our third hypothesis, we could demonstrate that the effect of self-generated predictions on task-switching performance is stronger than that of cue-induced expectations. In addition to self-generated predictions, we also looked at the impact of external cues, comparing their effects in a within-subjects design. We thereby expanded the study by Duthoo et al. (2012) and were able to distinguish the internal aspect from the verbal aspect in predictions. As noted before, verbalizing itself can lead to improved performance, in single-task as well as in task-switching paradigms. When reading aloud word cues presented on screen, participants can benefit from the additional articulatory process as well as the auditory input (Kirkham et al., 2012). By keeping these processes equal between both expectation conditions in our study, we were able to pinpoint the genuine influence of internally generated expectation. The effects of self-generated predictions reported here are therefore not due to artifacts of our verbalization procedure. When taken together with the results by Duthoo et al. (2012), we can argue that the impact of self-generated predictions is not limited to a specific experimental procedure. It can be obtained by manual predictions as well as verbal predictions (receiving an additional boost from the latter).

A stronger effect of self-generated predictions on task-switching performance compared to cue-induced expectations is in line with studies on internal vs. external sources of preparation. Arrington and Logan (2004) demonstrated that even if participants themselves decide when to repeat or switch tasks, alternations take longer than repetitions. At a long response-stimulus interval (1,000 ms) however switch costs were smaller than at a short interval (100 ms). The authors describe their findings "more compatible with active than with passive processes" (Arrington & Logan, 2004, p. 614). As these processes, such as the decision about which task to perform and the subsequent reconfiguration (cf. Logan & Gordon, 2001), need some time, preparation is more complete at the long interval.

In an attempt to investigate type-specific effects of foreknowledge on task switching Kleinsorge & Gajewski (2008) examined task performance based on externally presented versus internally generated information and additionally varied the reliability of foreknowledge. They found equal switch costs for externally induced and internally generated expectations when foreknowledge was reliable (although RTs for externally based foreknowledge were numerically smaller) but faster RTs for internally generated expectations when foreknowledge was unreliable. These findings suggest that at least with unreliable foreknowledge internally based expectations lead to more efficient task preparation than externally based foreknowledge. However, since this design used only short sequences, it might be possible that participants in the cue condition additionally learned the task order implicitly and thus profited from extra-cuing when foreknowledge was reliable but had more difficulties when order and pre-cue announced the wrong task.

Stronger effects on preparation of self-generated compared to cue-induced expectations were also found in a recent study at our lab (Kemper et al., 2012) in a simple two-choice task. Similar to the present study, participants were asked to either freely generate a prediction or read aloud a word cue denoting the upcoming stimulus. Correct predictions not only resulted in faster responses than correct cues, they also differed substantially on several ERP components. We found a larger mismatch-related negativity for predictions in the N2 component, suggesting that preparing for a self-generated prediction involves endogenous attention processes to a greater degree as preparing for a cued stimulus. We were also able to demonstrate a frequency-independent influence of subjective expectation on the P3 component, with an earlier peak for correctly predicted stimuli, indicating a speeded uncertainty resolution compared to the cueing condition. As there were no differences between expectation types in the lateralized readiness potentional (LRP), the influence of subjective expectation seems to be located in premotoric processing stages.

Conclusion

Subjective expectation plays a central role in our behavior by affecting a range of preparatory processes (cf. Umbach et al., 2012; Kemper et al., 2012). When researching expectation effects on behavior, it is important to allow participants to form their own expectations. Subjective expectation can be based on experienced frequency information in the task at hand (cf. Umbach et al., 2012). It can also be biased by previous experience in other environments (cf. Ayton & Fischer, 2004). Expectations triggered by external cues do not carry the same impact on premotoric preparatory processes and behavioral output as self-generated expectations (cf. Kemper et al., 2012). This is true not only for expectations regarding single-task stimuli (Umbach et al., 2012; Kemper et al., 2012), but also for task-switching paradigms. Self-generated expectations enable task-set preparation to a higher degree than cue-induced expectations, as the current results show. When relying on their subjective expectation, people are able to overcome the commonly found reluctance to switch tasks and prepare for every possibility alike. Had the young trolley driver in the example cited in the introduction expected a red light, could he have possibly been prepared to brake and avoid the accident? While texting and driving is probably always a bad idea, our findings suggest that people can prepare for (sudden) changes when they're within their expectations. To understand task-switching performance, it's not enough to look at the current (or recent) stimulation. It is important to account for internal subjective expectation as well.

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Figures

Figure 1

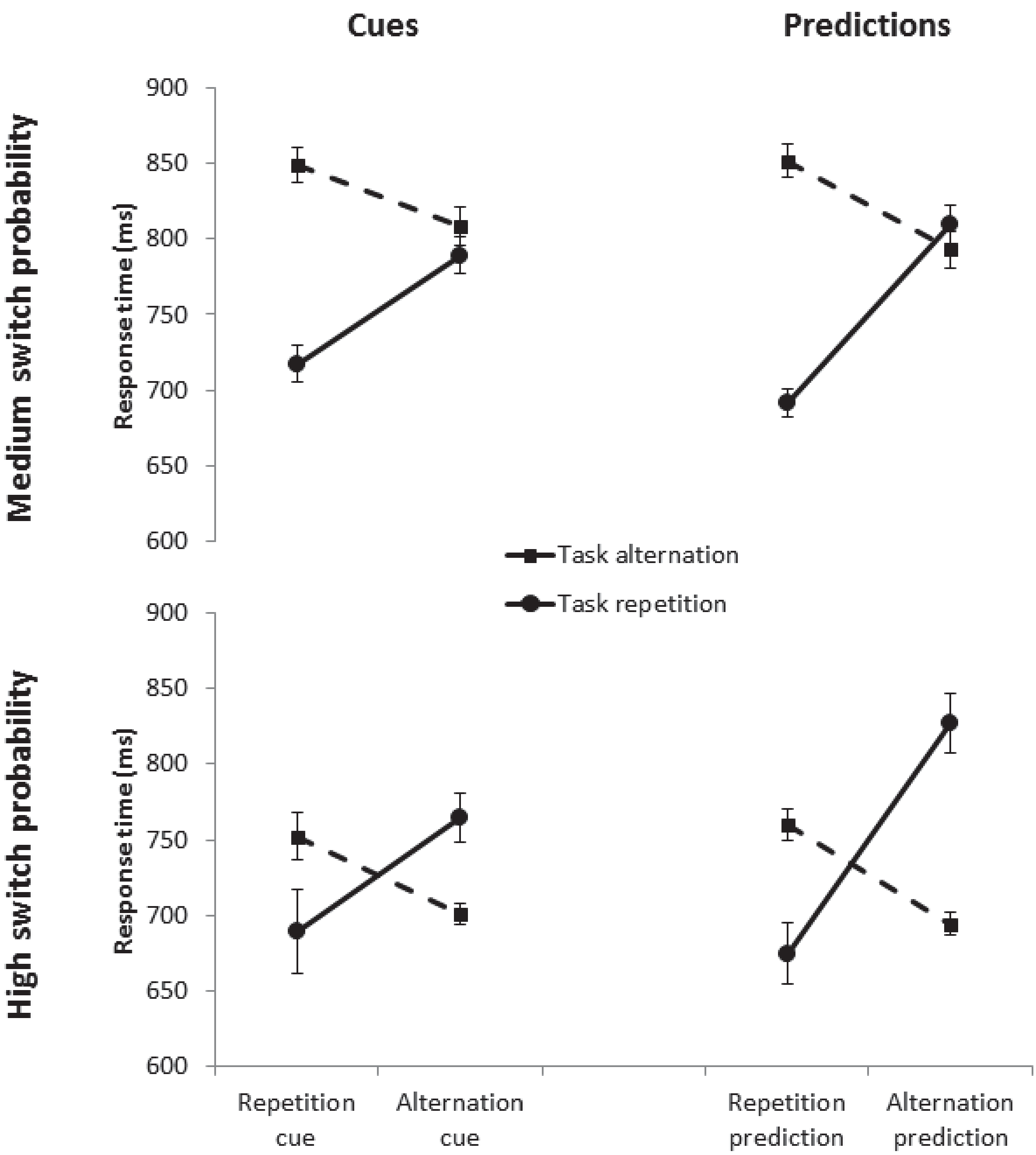

Figure captions

Figure 1. Mean response times (in milliseconds) for task alternations (dashed line) and task repetitions (solid line) following repetition and alternation cues (left) or predictions (right), separately for medium (50%, top) and high switch probability (80%, bottom). Error bars represent 95% confidence intervals around the mean (Cousineau, 2005; Morey, 2008; Baguley, 2012).