Feedback Interval Influences Feedback Processing: Behavioral and Electrophysiological Evidence

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Abstract

Feedback plays a crucial role in real life, and learning through feedback information constitutes an effective means for humans to acquire knowledge and skills. Feedback interval refers to the temporal delay between an individual' s behavior and the presentation of feedback stimuli. In the process of feedback processing, feedback interval represents an important influencing factor; however, research findings regarding its effects on feedback processing have been inconsistent. Behavioral and electrophysiological studies on the influence of feedback interval on feedback processing are introduced respectively, and the reasons for the differences in results are analyzed and summarized. Future research should consider integrating behavioral and electrophysiological approaches and standardizing the operational definition of feedback interval.

Full Text

Abstract

Feedback plays a crucial role in real life, and learning through feedback information is an effective means for humans to acquire knowledge and skills. Feedback interval refers to the temporal delay between an individual' s action and the presentation of feedback stimuli. In the process of feedback processing, feedback interval is an important influencing factor, yet research findings on how feedback interval affects feedback processing have been inconsistent. This paper introduces behavioral and electrophysiological studies on how feedback interval influences feedback processing and analyzes the reasons for discrepancies in results. Finally, we propose the necessity of standardizing the definition of feedback interval and combining behavioral and electrophysiological methods in future research.

Keywords: feedback interval; feedback processing; feedback-related negativity; delayed feedback; immediate feedback

1 Behavioral Research

Over the past half-century, behavioral research on how feedback interval influences feedback processing has accumulated substantial findings. Researchers have employed diverse learning tasks in these studies. Since the three components of feedback processing—task requirements, feedback, and subsequent behavioral adjustment—interact and influence one another, different tasks should affect feedback processing and learning outcomes. Therefore, distinguishing among different types of learning tasks is necessary for investigating the impact of feedback interval on feedback processing. This section categorizes the learning tasks in behavioral research into three types: category learning tasks, factual information learning tasks, and motor skill learning tasks, discussing how feedback interval affects feedback processing under each condition.

1.1 Feedback Interval Influences Category Learning

Category learning is the process by which organisms classify objects in their environment and determine appropriate responses based on formed category knowledge (Liu, Mo, & Zhang, 2007). In category learning research, Ashby, Alfonso-Reese, Turken, and Waldron (1998) designed two category structures: rule-based category structure and information-integration category structure. Experimental materials consisted of grating patterns varying in spatial frequency and orientation. Rule-based category structures rely on classification rules that consider only one dimension—either spatial frequency or orientation—whereas information-integration category structures require integrating both dimensions (Maddox, Ashby, & Bohil, 2003; Maddox & Ashby, 2004; Zhang & Liu, 2007; Sun & Xing, 2014).

Researchers propose that learning these two category structures is mediated by different systems (Maddox et al., 2003; Maddox & Ashby, 2004; Sun & Xing, 2014). Rule-based category learning is controlled by an explicit hypothesis-testing system, influenced by working memory and executive attention (Liu et al., 2014). People can even learn rule-based category structures without feedback (Ashby, Queller, & Berretty, 1999), so feedback interval does not affect rule-based category learning (Maddox et al., 2003). However, information-integration category learning is controlled by an implicit system primarily modulated by the tail of the caudate nucleus. Delayed feedback provides unexpected reinforcement to this implicit system, causing dopamine release from the substantia nigra into the tail of the caudate nucleus, which strengthens recently active synapses. Since dopamine-modulated learning requires tight coupling between stimulus-response and feedback, delayed feedback adversely affects learning performance (Maddox et al., 2003; Liu et al., 2014).

For example, Maddox et al. (2003) investigated how feedback interval affects rule-based and information-integration category learning. Experimental conditions were divided into delayed feedback and immediate feedback groups. The immediate feedback group received feedback 500 ms after response termination, while the delayed feedback group received feedback after 2500 ms, 5000 ms, or 10000 ms. Results showed that feedback interval did not affect rule-based category learning but impaired information-integration category learning, with accuracy significantly lower under delayed feedback conditions.

Because information-integration category learning is dopamine-modulated, Worthy, Markman, and Maddox (2013) proposed that learning is optimal when peaks in dopamine and calcium concentration occur 500 ms after the response. Using the same grating pattern materials, they set delay times at 0 ms, 500 ms, and 1000 ms to examine how different feedback intervals affect category structure learning. Results confirmed that delayed feedback did not affect rule-based category learning, but a 500 ms delay produced better performance on information-integration category learning than 0 ms or 1000 ms delays.

Xing, Wang, and Huang (2018) investigated how feedback interval affects probabilistic category learning using a weather prediction task. Participants were shown cards with unique geometric patterns and asked to predict whether each card represented "sunny" or "rainy" weather, with actual outcomes determined by preset probabilities. Participants made predictions and received feedback after an interval, with conditions of immediate feedback (500 ms) and delayed feedback (5000 ms). Results showed that immediate feedback produced better learning than delayed feedback, indicating that delayed feedback impairs probabilistic category learning. Participants used both explicit and implicit systems during learning but relied more on implicit learning.

Thus, in category learning, feedback interval plays different roles. It does not affect learning processes controlled by the explicit hypothesis-testing system but impairs learning controlled by the implicit system.

1.2 Feedback Interval Influences Factual Information Learning

In studying factual information learning, researchers investigate whether delayed feedback reinforces initially correct responses (Smith & Kimball, 2010; Butler et al., 2007) or corrects erroneous responses (Pashler et al., 2005).

Early researchers believed feedback reinforces initially correct responses, so shorter intervals between response and feedback should strengthen correct behavior, while information delay would weaken the response-feedback association and impair learning. For example, Saltzman (1951) used a "verbal maze"task and Bourne (1957) used a concept identification task to investigate delayed feedback effects, finding that delayed feedback increased error rates and reduced learning performance.

As research progressed and experimental paradigms multiplied, researchers suggested that advantages of delayed feedback might only emerge after extended periods. For instance, Butler et al. (2007) found positive effects of delayed feedback on long-term memory using a factual information learning task. Materials consisted of 12 articles, with factual information from each selected as test items in multiple-choice format (one question, one correct answer, and five incorrect answers). The immediate feedback group received feedback immediately after completing the multiple-choice items, while the delayed feedback group received feedback during a second study session one day later. A final cued-recall test one week after completion revealed that delayed feedback benefited long-term memory more than immediate feedback, with no effect on error correction. Conditional analysis indicated that delayed feedback better reinforced initially correct responses than immediate feedback.

Similarly, Smith and Kimball (2010) tested immediate versus delayed feedback on factual information learning, proposing that feedback is a mechanism for reinforcing initially correct responses. Using 76 trivia facts as materials, the experiment had two phases: a 60-minute learning phase (study + initial test) and a 30-minute delayed test phase one week later. The immediate feedback group received feedback right after the initial test, while the delayed feedback group received feedback 8 minutes after the initial test. Results showed that the delayed feedback group performed better on the test one week later, and delayed feedback increased the probability of repeating initially correct responses compared to immediate feedback. Feedback interval did not significantly affect error correction.

Researchers suggest that providing delayed feedback after correct responses functions like spaced restudy, while delayed feedback after errors reduces competition between erroneous and correct responses, allowing errors to extinguish and facilitating correct response learning (Kulhavy, 1977; Smith & Kimball, 2010; Butler et al., 2007).

Pashler et al. (2005) also acknowledged the beneficial effects of delayed feedback but explained it from the perspective of error correction. They studied how immediate versus delayed memory testing affects foreign language learning. Materials included 20 Luganda words and their English translations, with participants learning the Luganda words and remembering their English equivalents, then writing the English translations during testing. The experiment had practice and test phases separated by one week. The practice phase included two presentations and two tests of all words with feedback, while the final test phase one week later had no feedback. Five feedback types were compared: (1) immediate feedback (0 ms delay), (2) 5000 ms delay (blank screen), (3) 5000 ms presentation of "correct" or "incorrect," (4) 5000 ms presentation of the correct answer, and (5) no additional testing on day one. Results showed that only feedback type (4) improved performance across the two practice tests and yielded an advantage on the final test. Moreover, when learners responded correctly, feedback timing did not affect test performance. Therefore, the researchers argued that in difficult tests, delayed feedback improves performance because the initial error is often forgotten during the delay interval, reducing interference with learning the correct response from feedback. Learners receiving immediate feedback experience interference from their incorrect responses (Guthrie, 1971).

Furthermore, the lack of an established operational definition for feedback interval represents a major potential cause of inconsistent findings (Smith & Kimball, 2010), particularly prominent in factual information learning research. In educational contexts, immediate feedback is defined as providing answers immediately after students respond, while delayed feedback means providing answers after students have answered several additional questions (Sinha & Glass, 2015). However, in actual implementation, immediate and delayed feedback are subdivided into many types. Immediate feedback can be given after each question, at the end of each module, or immediately after each test, while delayed feedback can be provided after seconds, hours, the next day, or within a week. Therefore, defining feedback interval to meet most research needs remains a challenging research endeavor. Additionally, during delayed feedback, participants' expectations and curiosity about answers (Mullaney, Carpenter, Grotenhuis, & Burianek, 2014) also influence results.

1.3 Feedback Interval Influences Motor Skill Learning

Early motor skill learning research also suggested that delayed feedback disrupts the action-outcome connection, impairing motor skill learning, so immediate feedback should be more beneficial (Salmoni, Schmidt, & Walter, 1984). Later research found that motor skill learning can be divided into acquisition, retention, and transfer phases, with delayed feedback set at different phases producing different final learning outcomes (Lee, Swinnen, & Serrien, 1994; Jin, Zhang, Sun, & Ren, 2001). Additionally, motor skill complexity also affects learning outcomes (Feng, Feng, & Feng, 2018).

Jin et al. (2001) required participants to aim at targets using a sighting device, providing immediate feedback or feedback delayed by 2000 ms, and set up no-feedback retention tests the day after the experiment and transfer tests on the third day to explore feedback interval effects on motor skill learning. Results showed that during the acquisition phase, immediate feedback improved tracking accuracy more than 2000 ms delayed feedback. However, delayed feedback during acquisition improved retention test performance, while feedback interval did not affect transfer.

During the motor skill acquisition phase, Feng et al. (2018) further investigated how feedback interval affects motor skills under different task difficulties. The complex task used a two-dimensional tracking task where participants tracked a moving ball on a computer screen, with feedback provided immediately or delayed by 4000 ms. Results showed no effect of feedback interval on motor skill learning. The simple task required participants to manipulate a ball to stop near a target position, with feedback also provided immediately or delayed by 4000 ms. Results showed that immediate feedback produced better accuracy than delayed feedback. Therefore, during the motor skill acquisition phase, feedback interval effects depend on task difficulty: feedback interval does not affect learning of complex tasks, but immediate feedback benefits acquisition of simple tasks within a certain timeframe.

1.4 Summary

The above three sections presented behavioral research on how feedback interval influences feedback processing, yet findings remain difficult to reconcile. Below we attempt to analyze reasons for these inconsistencies.

One reason is that experimental tasks involve different memory types, which may contribute to inconsistent results. For example, category learning tasks involve working memory (Maddox et al., 2003; Maddox & Ashby, 2004), factual information learning tasks primarily involve declarative memory (Butler et al., 2007; Mullaney et al., 2014), and motor skill tasks involve procedural memory (Jin et al., 2001). Future research that carefully distinguishes the memory types involved in different experimental tasks and conducts more refined analyses may help clarify how feedback interval influences feedback processing.

Another reason is inconsistent operational definitions of feedback interval. Each study establishes its own criteria for delayed versus immediate feedback. Smith (2007) proposed that in behavioral research, operational definitions of feedback interval could be categorized into four types based on researchers' focus: Item-by-item immediate (IBI-I) feedback (provided immediately after each test trial); Item-by-item delayed (IBI-D) feedback (provided after a delay following each test trial); End-of-test immediate (EOT-I) feedback (provided immediately after completing all test items); and End-of-test delayed (EOT-D) feedback (provided after completing all test items and an additional interval). However, this still cannot fully explain all experimental tasks in the feedback interval literature. Researchers define immediate and delayed feedback differently based on their research purposes and methods, with delayed feedback always defined relative to immediate feedback. Therefore, inconsistent operational definitions of feedback interval also contribute to discrepancies.

2 Electrophysiological Research

With the rise of cognitive neuroscience, researchers have begun exploring the neurophysiological mechanisms underlying feedback interval effects on feedback processing. Event-related potential (ERP) research has identified the feedback-related negativity (FRN) as closely associated with feedback. Below we detail this component and review findings from studies using it to investigate feedback interval effects.

2.1 Introduction to Feedback-Related Negativity

For investigating how feedback interval influences feedback processing and learning, ERP technology offers unique advantages due to its millisecond-level temporal resolution (Kim & Arble, 2019). Among ERP components, FRN is the primary measure for studying feedback processing and learning (Luft, 2014).

FRN is an ERP component evoked by negative feedback such as behavioral errors or monetary losses, typically peaking 250-350 ms after feedback presentation (Miltner, Braun, & Coles, 1997). Research shows that FRN is sensitive to feedback valence, with negative feedback eliciting significantly more negative FRN than positive feedback (Gehring & Willoughby, 2002; Hajcak, Moser, Holroyd, & Simons, 2006; Walsh & Anderson, 2012; Sambrook & Goslin, 2015). Additionally, FRN is sensitive to expectancy violation: when actual outcomes mismatch predictions, both positive and negative feedback elicit FRN, with amplitude related to the degree of expectancy-feedback mismatch (Oliveira, Mcdonald, & Goodman, 2007; Ferdinand, Mecklinger, Kray, & Gehring, 2012). Recent studies have examined how different feedback intervals affect FRN to explore underlying neural mechanisms (Foerde, Race, Verfaellie, & Shohamy, 2013; Foerde & Shohamy, 2011; Weinberg, Luhmann, Bress, & Hajcak, 2012; Weismuller & Bellebaum, 2016).

FRN-based research on feedback processing can be divided into two categories: feedback evaluation and feedback learning. Feedback evaluation studies typically use simple gambling tasks where positive and negative feedback probabilities are usually 50% and randomly presented, meaning participants' behavioral responses are not necessarily linked to feedback and participants cannot learn patterns from feedback to adjust subsequent behavior. Therefore, participants' performance does not improve gradually, and they remain in the feedback evaluation stage without learning. In contrast, feedback learning studies focus not on feedback evaluation itself but on behavioral adjustment based on feedback information (Luft, 2014). In feedback learning tasks (e.g., probabilistic learning tasks), tasks are learnable and participants can gradually improve performance based on feedback. Recent studies have begun examining how feedback interval affects both types of research, discussed below.

2.2 Feedback Interval Influences Feedback Evaluation

Weinberg et al. (2012) were among the first to use FRN to study delayed feedback effects on feedback evaluation, employing a modified gambling task: two identical door patterns appeared on screen, and participants chose one, receiving feedback after a 1000 ms (short delay) or 6000 ms (long delay). Results showed that in the short delay condition, loss feedback elicited larger FRN, but in the long delay condition, no significant FRN was elicited—the difference between win and loss feedback was negligible. This may indicate that delaying feedback interferes with forming action-outcome associations, preventing people from connecting actions with outcomes delayed by several seconds, or that different systems process immediate versus delayed rewards.

However, Wang, Chen, Lei, and Li (2014) obtained different results. Using a simple gambling task with four differently colored balloons, participants selected one balloon. Before balloon presentation, a star or triangle indicated delay duration: 600-1000 ms for short delay and 4000-5000 ms for long delay. Feedback was presented as smiley or frowning faces representing wins or losses. Contrary to previous findings, this study found FRN was elicited in both long and short delay conditions with no significant amplitude differences. This suggests that waiting time did not affect participants'responses and that early feedback-related brain activity was equivalent across conditions.

Researchers suggest that differences in experimental procedures and delay interval settings may account for these discrepancies (Weismuller & Bellebaum, 2016). Holroyd, Krigolson, Baker, Lee, and Gibson (2009) proposed that FRN reflects prediction error, particularly when feedback is useful for learning. However, in both experiments above, feedback valence was randomly presented and non-instrumental, preventing participants from learning patterns from feedback, which may explain inconsistent findings (Peterburs, Kobza, & Bellebaum, 2016).

2.3 Feedback Interval Influences Feedback Learning

Unlike feedback evaluation, feedback learning refers to learning from feedback outcomes to adjust behavior in subsequent trials. Different feedback intervals affect not only feedback evaluation but also feedback learning. Studies on feedback interval effects on feedback learning typically use probabilistic learning tasks or paired-association learning tasks, adjusting feedback intervals to observe learning phenomena and FRN changes.

Building on Weinberg et al. (2012), Peterburs et al. (2016) improved the experimental design, creating a probabilistic learning task with three delay durations to examine linear effects of increasing feedback interval on feedback learning. Materials comprised six Japanese characters presented one at a time, with participants responding via left or right button presses. After selection, the corresponding on-screen button turned green, and after a brief delay, correctness feedback was provided. Delay durations were 500 ms (short), 3500 ms (medium), and 6500 ms (long). Behavioral results showed that correct response proportions were unaffected by feedback delay. However, FRN difference wave amplitude decreased linearly as feedback interval increased, being largest in the short delay condition and smallest in the long delay condition.

These findings were replicated and extended. In 2016, Weismuller and Bellebaum conducted a more detailed study using a probabilistic learning task to examine whether FRN under delayed feedback is still affected by subjective reward expectation. Materials were five Japanese characters, each with different probabilities of winning money. Two characters were presented simultaneously, and participants guessed which would yield more reward. After a delay, win or loss feedback was provided. Feedback intervals were 1000 ms (immediate) and 7000 ms (delayed). Additionally, when participants made selections, a scale from 0 to 100% appeared between symbols, requiring participants to indicate their subjective reward expectation. Results showed that accuracy increased with learning, with blocks 3, 4, and 5 significantly more accurate than block 1, but feedback interval did not affect learning. Moreover, FRN difference wave amplitude was significantly larger in the immediate than delayed feedback condition, and in both conditions, FRN difference wave amplitude was larger for unexpected than expected outcomes, though subjective reward expectation was unaffected by feedback interval.

In addition to probabilistic learning tasks, Arbel, Hong, Baker, and Holroyd (2017) used a paired-association learning task and also found that immediate feedback elicited larger FRN. The task involved learning names (non-words) for 56 novel objects (non-objects) divided into four groups of 14 objects each. In each trial, participants saw a picture of a novel object and two possible names, selecting the correct name via button press. After a delay, correct or incorrect feedback was presented. Two groups received immediate feedback (500 ms after button press) and two received delayed feedback (6500 ms after button press). A follow-up test without feedback was administered one day later. Results showed that learning performance improved significantly across the experiment regardless of feedback interval, meaning feedback interval did not affect learning outcomes. Additionally, immediate feedback elicited larger FRN than delayed feedback.

Contrasting with studies finding no learning effects, some research suggests learning ability decreases as delay increases. Opitz et al. (2011) studied immediate versus delayed feedback effects on artificial grammar learning using an artificial grammar learning task. Materials were long sentences based on subject-verb-object structure. In the learning phase, participants observed sentences to learn basic grammatical rules. In the testing phase, they judged whether new sentences followed grammatical rules, receiving immediate (0 ms) or delayed (1000 ms) correctness feedback. Results showed that delayed feedback (accuracy = 0.683) impaired artificial grammar learning compared to immediate feedback (accuracy = 0.826), and feedback delay affected both FRN and P300.

Similarly, Yin et al. (2018) used a time estimation task to study delayed feedback effects on reinforcement learning. In this task, participants estimated 1000 ms after hearing an auditory signal and pressed a key. Feedback was either immediate (receiving "√" or "×" 600-1000 ms after response) or delayed (receiving feedback for the first trial only after the sixth trial, with five intervening trials to make participants forget their previous estimate). Results showed that in immediate feedback conditions, participants adjusted behavior better after negative than positive feedback, a pattern not observed in delayed feedback conditions. Additionally, the difference in PCA-FRN amplitude between positive and negative feedback was significantly smaller in delayed than immediate feedback conditions, though this difference was not significant in raw data. The study demonstrated that immediate feedback promotes retention of correct answers and adjustment of incorrect answers in reinforcement learning, while delayed feedback weakens the connection between outcomes and previous actions, impairing reinforcement learning.

2.4 Summary

Section 2 discussed electrophysiological research on how feedback interval influences feedback processing, categorizing studies into feedback evaluation and feedback learning, focusing primarily on how feedback interval affects learning outcomes and FRN amplitude.

Regarding feedback interval effects on learning outcomes, multiple factors may influence how delayed feedback affects learning. First, experimental task setup differs. For example, in probabilistic learning tasks, most studies find that feedback interval does not affect learning (Weismuller & Bellebaum, 2016; Arbel et al., 2017). Researchers suggest this is because in probabilistic learning tasks, the probability of feedback types for different stimuli remains constant, and learners likely master stimulus-response-outcome associations in the first block, making delayed feedback irrelevant in subsequent blocks (Peterburs et al., 2016). However, in Yin et al. (2018), the delayed feedback interval was set to provide feedback for the first trial only after five intervening trials, which acted as interference items that prevented learning from feedback and affected results.

Second, the degree of working memory involvement in learning tasks matters. In Opitz et al.' s (2011) artificial grammar learning task, participants had to memorize multiple grammatical rules during the delay, a high-demand task with substantial working memory involvement, so even brief delays impaired artificial grammar learning. In Weismuller and Bellebaum' s (2016) study, participants only needed to remember choices between two stimuli, requiring less working memory involvement, so feedback interval had minimal impact on learning outcomes.

Third, feedback interval duration settings vary. In electrophysiological research, some studies present feedback intervals randomly within a range (Wang et al., 2014), while others use fixed intervals (Weinberg et al., 2012; Weismuller & Bellebaum, 2016). Moreover, specific intervals for immediate and delayed feedback differ across studies. For example, Arbel et al. (2017) defined immediate feedback as 500 ms, Weismuller and Bellebaum (2016) set it at 1000 ms, and other researchers considered both 500 ms and 1000 ms as short delays (Weinberg et al., 2012; Peterburs et al., 2016). Delayed feedback intervals also range from 6000 ms to 7000 ms (Weinberg et al., 2012; Weismuller & Bellebaum, 2016; Arbel et al., 2017). These inconsistent interval settings also contribute to discrepancies.

Regarding feedback interval effects on FRN, findings also differ. Most studies agree that delayed feedback reduces FRN amplitude (Weinberg et al., 2012; Weismuller & Bellebaum, 2016; Arbel et al., 2017), while a few find no effect (Wang et al., 2014). Differences may stem from variations in experimental procedures and interval settings (Weismuller & Bellebaum, 2016) and individual differences (Zhang, Lei, Yin, Li, & Li, 2018). Future research should strictly control experimental procedures to examine how pure FRN amplitude changes with feedback interval duration.

Furthermore, when feedback interval affects FRN, differences between delayed and immediate feedback FRN suggest that systems processing delayed rewards may be separate from those processing immediate rewards (Weinberg et al., 2012). During learning, processing immediate versus delayed feedback involves different neural mechanisms: the striatum and medial temporal lobe (Foerde & Shohamy, 2011). The striatum supports feedback-based learning to promote stimulus-response associations (Gabrieli, 1998), while the hippocampus in the medial temporal lobe can bind related elements across time, linking temporally or spatially discontinuous experiential elements (Davachi, 2006; Staresina & Davachi, 2009), providing conditions for learning in delayed feedback environments. When learning requires more effort or involves conflicting information, these regions may operate in parallel and interact synergistically. As waiting time increases, striatal activity in feedback processing gradually decreases, with greater reliance on the hippocampus for declarative memory (Dickerson & Delgado, 2015; Foerde et al., 2013; Foerde & Shohamy, 2011).

3 Research Outlook

In the preceding sections, we addressed the question of how feedback interval influences feedback processing, reviewing behavioral and electrophysiological research. In summarizing behavioral studies, we discussed how feedback interval affects three types of experimental tasks and analyzed reasons for result discrepancies.

In category learning research, extending feedback interval does not affect explicit learning but impairs implicit learning (Maddox et al., 2003; Maddox & Ashby, 2004; Xing et al., 2018), with optimal implicit learning occurring at a 500 ms interval (Worthy et al., 2013). Most factual information learning studies find that delayed feedback yields better test performance than immediate feedback (Butler et al., 2007; Smith & Kimball, 2010; Mullaney et al., 2014). In motor skill learning research, during the acquisition phase, immediate feedback benefits simple tasks more than delayed feedback, but feedback interval effects are not significant for complex tasks (Feng et al., 2018). During the post-learning retention phase, delayed feedback better facilitates motor skill retention (Jin et al., 2001). We analyzed these discrepancies in terms of different memory types involved in experimental tasks and inconsistent operational definitions of feedback interval.

In summarizing electrophysiological research, we used FRN as the primary measure, dividing experimental tasks into feedback evaluation and feedback learning, and reviewed how feedback interval affects both. In feedback evaluation research, delayed feedback elicits smaller FRN amplitude than immediate feedback (Weinberg et al., 2012), though pre-task cueing (Wang et al., 2014) or individual differences (Zhang et al., 2018) may affect results. In feedback learning research, immediate feedback elicits significantly larger FRN amplitude than delayed feedback, and feedback interval does not affect probabilistic learning or paired-association tasks (Weismuller & Bellebaum, 2016; Arbel et al., 2017), but delayed feedback impairs reinforcement learning and artificial grammar learning (Yin et al., 2018; Opitz et al., 2011). These discrepancies may arise from multiple factors including experimental task setup, working memory involvement, and feedback interval settings.

Comparing results across behavioral and electrophysiological domains reveals that inconsistent processing stages may prevent direct comparison. Behavioral research focuses more on how feedback interval affects learning outcomes, with learning tests administered either on the experimental day or days later as memory retention tests (Smith & Kimball, 2010), using final test performance to estimate whether extending feedback interval during learning affects outcomes (Butler et al., 2007; Mullaney et al., 2014). Electrophysiological research focuses more on how feedback interval affects feedback evaluation itself, primarily examining feedback interval effects on FRN amplitude (Weinberg et al., 2012; Wang et al., 2014). Although some electrophysiological studies examine how feedback interval modulates feedback learning, common learning tasks include time estimation and probabilistic learning tasks (Yin et al., 2018; Weismuller & Bellebaum, 2016; Peterburs et al., 2016), which differ substantially from tasks used in behavioral research.

Future research should integrate behavioral and electrophysiological approaches based on their respective strengths. Behavioral research findings should guide electrophysiological research, particularly regarding how feedback interval affects learning outcomes. Electrophysiological research should leverage its advantages in revealing neural mechanisms and cognitive timing to validate behavioral findings and further elucidate the cognitive and neural mechanisms underlying feedback interval effects on feedback processing and learning.

Additionally, experimental tasks need to be distinguished by memory type, and operational definitions of feedback interval must be standardized. As previously analyzed, different memory types and definitions of feedback interval both contribute to inconsistent results. Therefore, future research should establish standards for feedback interval definitions and memory types involved in learning tasks to better differentiate how feedback interval affects different task types.

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Note: Figure translations are in progress. See original paper for figures.