# Evaluation of the Interplay between Feedback Processing and Implicit Learning: A Neuroimaging Approach.

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# 論 文 内 容 要 旨


Skills are techniques of body or mind (motor or cognitive skills) learned by training. The unique feature of skill learning is that verbalization of skills is difficult because skills are tacit knowledge and acquired implicitly. The importance of the role of skilled performance in society has been widely recognized. The absence of proper training can lead to skill gaps in key positions that can negatively affect overall profitability. Skill learning is also important in controlling complex systems considering that human error has been cited as a cause or contributing factor in disasters and accidents in industries as diverse as nuclear power plant, aviation, space exploration, and medicine.

One of the key foundations for successful skill learning is feedback-based learning which refers to our ability to use performance feedback in subsequent behavior. In psychological studies of human behavior, the term feedback describes stimuli used to signal performance accuracy, which can then be used to modify future performance. Although feedback is among the major influences, the type of feedback and the way it is given can be differentially effective. On the other hand, learning also affects the way we process the external feedback. At the beginning of learning, one has no prior knowledge about the stimulus-response-outcome associations and therefore the decisions have no basis, while after learning, s/he make decisions based on a learned stimulus-response-outcome association. Therefore, feedback has a different role at the beginning of learning compared to the feedback after learning which provides a true assessment of the task.

In this study, the interplay between feedback processing and learning during implicit learning has been evaluated. In order to analyze the interplay between feedback processing and learning, four issues have been investigated:

1. How do different types of feedback (positive vs. negative feedback) affect the learning process in terms of performance and neural networks?
2. How does human process positive and negative feedback during the course of learning?
3. How does learning process affect the way we process the feedback?
4. How do we use the knowledge we have learned from positive and negative feedback in novel situations? In other words, how do different types of feedback guide our decision making?

stimuli and outcomes on the basis of provided feedback and (2) A sugar production factory paradigm (SPF) in which subjects learn implicitly from their previous experience to control the output production of a factory near a prespecified target level.

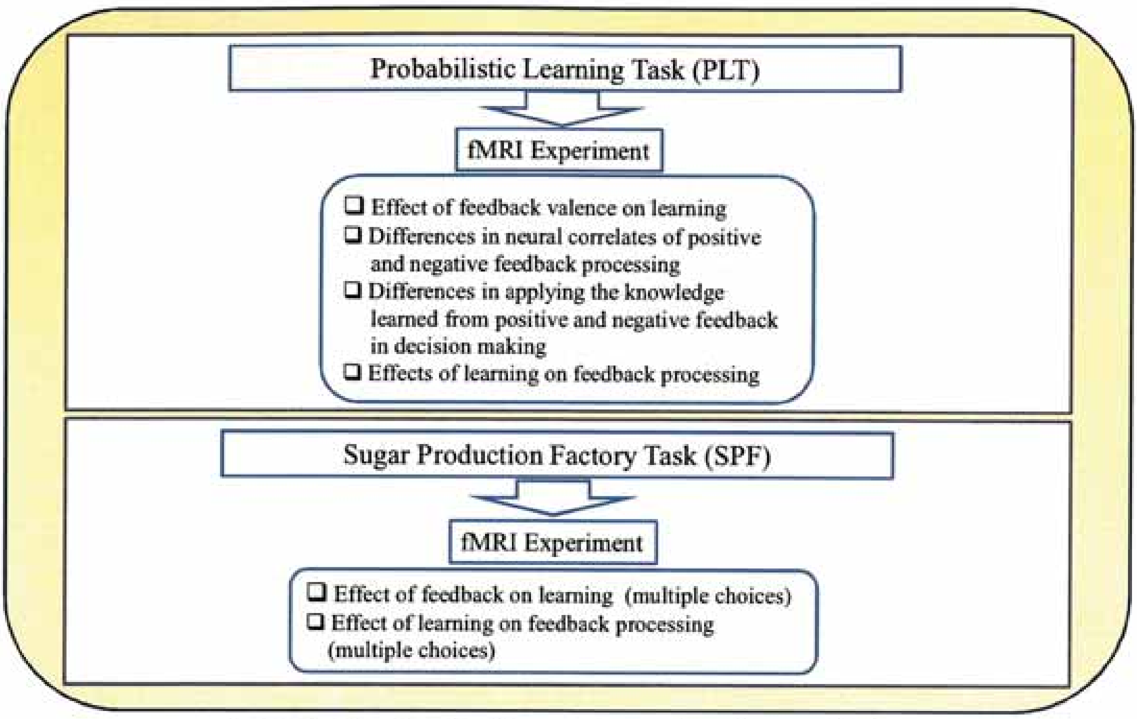


Fig.1 Learning Paradigm and neroimaging methods

Regarding the first question, an fMRI experiment has been performed based on the PLT paradigm and two goals have been pursued:

1. Behavioral differences in learning from positive and learning from negative feedback.
2. Investigating neural correlates of learning from positive feedback only and learning from negative feedback only.

The result showed that valence of the provided feedback (positive or negative) does not affect subjects' performance. The fMRI results showed specific involvement of medial frontal cortex in early stage of learning from negative feedback; implying that this brain region is involved in the acquisition of learning from negative experiences. The results also showed the involvement of right orbitfrontal cortex after learning in positive-only feedback condition suggesting that this brain region is more important in expression of learning, possibly by guiding behavior during decision making in late stage of learning through its strong connections with striatum.

To answer the second question, the neural correlates of positive and negative feedback processing during the course of learning the PLT task have been examined using fMRI. Using the unique design of the task the differences in how human brain processes positive and negative feedback when s/he receives positive-feedback only negative-feedback only, or both positive and negative feedback have been identified. The most important finding in this part was that the neural correlates of positive and negative feedback processing in full feedback condition was different from those observed in positive-only and negative only feedback conditions. Regarding the positive feedback processing, the observed neural activity was consistent with the results of previous neuroimaging studies; suggesting the involvement of dorsal striatal regions in positive feedback processing. Regarding the negative feedback processing, the results suggest a new role for the medial orbitofrontal cortex, i.e. negative feedback processing. Specifically, I speculate that this brain region along with the medial temporal structure plays an important role in memory operations related to non-awraded stimuli. Comparing neural correlates of negative feedback processing with positive feedback processing in full feedback condition suggest the involvement of posterior medial frontal structure in learning from errors rather than conventional error processing role that has been suggested by previous studies. However, no significant activity in these brain regions has been observed when comparing positive and negative feedback processing in FBN and FBP conditions.

To answer the third question, I investigate the changing role of feedback during a goal-directed implicit learning paradigm in which subjects learn associations between responses and the incentive value of outcomes while they make decisions to reach a goal and receive feedback on the outcome of their efforts along the way. SPF task, as a goal-directed implicit learning paradigm, in conjunction with event-related fMRI has been used. The results suggest the involvement of right SFG in positive feedback processing in exploratory phase of learning that explains learning-related decrease in activity of this region observed previously in implicit learning studies. The results also suggest that observed learning-related increase in precuneus activity in previous implicit learning studies could arise from the specific role of this brain region in negative feedback processing after learning. Besides clarifying the role of right SFG and precuneus in implicit learning, the results revealed the important role of positive and negative feedback in early and late stages of learning, respectively.

Regarding the last question, our results challenge the previous interpretation of the test-phase results of the PLT task. The results add more insights into the understanding of value-based decision making and suggest that (1) reinforcement function is characterized by a concave function of cognitive feedback probability, even in the absence of primary or secondary rewards; a finding that implies the difficulty in differentiating between two most-often rewarded stimuli, and (2) the shape of the utility function for reinforcements and punishments are not the same (more concave for reinforcements than punishments) even when the reinforcements and punishments are in the form of positive and negative outcome feedback; implying that discriminating between two frequently-punished stimuli is a little bit easier than differentiating between two frequently-rewarded stimuli.

In summary, this study made use of neuroimaging techniques, in conjunction with novel experimental designs, for investigating the interplay between feedback processing and skill learning. Considering the importance of learning in society (schools, companies, industries, etc.) and the existence of controversy about the efficient way of skill learning and training, the results showed that neuroimaging can be quite helpful for clarifying the inconsistencies. Evidence from cognitive neuroscience, in particular, might provide a way to advance the science of education and learning; a promising direction toward improving the education policy in schools and industries.

The results of this study have several implications. First, understanding the cognitive role of the brain regions specific to learning from positive and negative feedback may ultimately help us to improve the learning process by augmenting the related cognitive processes (e.g. attention, motivation, etc.) in application. For example, recent evidence suggest the involvement of dopaminergic signaling (which is specific to learning from positive feedback) in improving the attentional mechanisms; an idea that may explain how positive feedback influence the learning process. Therefore, training procedures or educational systems that improve the involvement of attentional systems during learning will be more effective.

Second, I found that the neural correlates of positive and negative feedback processing in full feedback condition was different from those observed in positive-only and negative only feedback conditions. This finding suggests that the schedule of providing positive and negative feedback can be optimized for efficient training. The question that arises is how this schedule can be optimized? The results of this study regarding the effect of learning on feedback suggest that providing more positive examples in the early stage of training whereas focusing more on negative examples in the late stage of training could be more efficient.

Besides these implications, it should be mentioned that further steps are needed to apply these results for realistic applications. The findings of this study are based on a number of simple cognitive tasks that may not include all the aspects of tasks that are performed in real situations like power plants or other complex systems. Therefore, to be applicable to real world situations, future studies are required to verify the applicability of the findings of this study in more ecologically valid situations.

# 論文審査結果の要旨

本研究では、大規模システムの運転等において重要な役割を果たす「スキル」の学習過程に着目し、学習者に対するフィードバックの影響を中心に脳科学的見地からの検討を行い、スキル学習の効率を上げるための知見を明らかにしている。スキル学習ではフィードバックに基づく学習が重要な役割を果たしているが、正のフィードバック（正解を強調する方法）と、負のフィードバック（誤りを強調する方法）が、正、負のフィードバックがスキル学習に対してどのような効果の違いをもたらすか、それが脳科学的にはどのような違いがあるのかということは明らかになっていない。本研究では二つの実験パラダイムと機能的核磁気共鳴法(fMRI)を用いて、フィードバックの種類が学習に与える影響、人間が学習過程においてフィードバック情報を処理する方法、学習プロセスのフィードバック処理への影響、そして正のフィードバックと負のフィードバックで学習して得られた知識による意志決定過程の違いについて検討を行っており、全文８章からなる。

第１章は序論であり大規模システムの運転におけるスキル学習とフィードバックの重要性と本研究の目的を述べている。

第２章では、本研究において重要な意味を持つ脳科学的研究手法に関して、その原理と実験方法に関して述べている。

第３章では、本研究で用いている二つの実験パラダイム（確率的学習タスク：PLT と砂糖工場タスク：SPF）について述べている。

第４章では、PLT を用いて正負のフィードバックの学習効果への影響を検討し、学習効果に関しては差異がないこと、及びそれぞれのフィードバックによる学習後の意志決定において関連する脳機能部位を明らかにした。

第５章では、正負のフィードバックを厳密に分離して制御する PLT を用いて、人間が学習過程においてフィードバックを処理する方法に関して脳科学的な検証を行い、正負のフィードバック学習が関連する脳機能部位を明らかにした。

第６章は、SPF により学習プロセスのフィードバック処理への影響の検証を行っており、スキル学習における探索フェーズと学習後のフェーズにおける関連する機能部位を明らかにしている。

第７章は、PLT を用いて正負のフィードバックに基づいて学習して得られた知識による意志決定過程の違いについて検討を行い、これまでの解釈に誤りのある可能性を指摘している。

第８章は結論である。

以上要するに本論文は、大規模システムの運転等において重要な役割を果たす「スキル」の学習過程の脳科学的側面からの理解向上を実現しており、今後の安全工学の向上に資するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。