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A Survey of Multimodal Systems and Techniques for Motor Learning

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Abstract

This survey paper explores the application of multimodal feedback in automated systems for motor learning. In this paper, we review the findings shown in recent studies in this field using rehabilitation and various motor training scenarios as context. We discuss popular feedback delivery and sensing mechanisms for motion capture and processing in terms of requirements, benefits, and limitations. The selection of modalities is presented via our having reviewed the best-practice approaches for each modality relative to motor task complexity with example implementations in recent work. We summarize the advantages and disadvantages of several approaches for integrating modalities in terms of fusion and frequency of feedback during motor tasks. Finally, we review the limitations of perceptual bandwidth and provide an evaluation of the information transfer for each modality.

Keywords

Augmented Motor Learning and Training, Multimodal Systems and Feedback, Rehabilitative Technologies

1. Introduction

Throughout the last decade, many advancements have been made in the design of automated systems to support motor learning, particularly in rehabilitative scenarios. This has led to the creation of a myriad of systems ranging from virtual reality to robotics to serious games and beyond to support the motor learning process in both clinical and home learning environments. Automated motor learning is a two-way process where the system must learn an individual's motor performance by sensing, processing, and recognizing movement information in three-dimensional (3D) space, while the individual must understand and improve his or her performance based on real-time assessment information delivered by the system during exercise. This leads to several questions related to the design of multimodal interaction in the production of systems for motor learning, which are as listed below.

1. **Delivery Mechanism:** How should the user interact with the system?
2. **Sensing Mechanism:** How should the system capture and process the user's motion?
3. **Modality Selection and Mapping:** How should each modality be used to provide feedback?

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4. **Multimodal Integration:** How should multiple modalities of feedback be combined and when should they be presented to best support motor learning?
5. **Perceptual Bandwidth and Information Transfer:** What are the perceptual limitations of each modality and how can their effectiveness be measured?

This survey explores the above questions by reviewing and summarizing popular techniques that have been developed for transmitting motor information through haptic, visual, and auditory modalities in real time. The advantages and disadvantages of various approaches are presented with an emphasis on motor task complexity and the user's proficiency in learning a motor task. The paper is organized as follows: Section 2 covers a general review of multimodal learning systems in terms of delivery and sensing mechanisms, particularly in the context of rehabilitation, as it is perhaps the most common application area for these systems. The advantages and limitations of each approach are also presented for comparison. In Section 3, recent findings presented in other studies on modality selection and mapping are discussed, including the best practices for implementation in each modality for increasing motor task complexity. In Section 4, approaches for multimodal integration are presented, including the fusion of modalities as well as the frequency and timing of feedback presentation. Section 5 presents a brief overview of perceptual bandwidth and information transfer as considerations for evaluating the effectiveness of each modality in research. We conclude in Section 6 with the challenges that remain for future work in this field.

2. Multimodal Learning Systems

2.1 Feedback Delivery Mechanisms

Perhaps the most popular application for motor learning is the domain of rehabilitation, where a vast multitude of systems have been applied over the last several decades. While many mechanisms for feedback delivery in these systems exist, two of the most overwhelmingly popular mechanisms in research include virtual reality (VR) and serious games. In this section, we summarize some of the major research findings in these two areas.

2.1.1 Virtual reality

Due to the ability of VR environments to frame motor tasks into problem-oriented scenarios to successfully support learning across a broad variety of exercises, they have been the most well-explored medium for information delivery in motor learning research, particularly in rehabilitation [1]. A review of these environments by Holden [2] indicates that one of their primary advantages is the direct transfer of learning in the virtual environment to real-world tasks. Holden's review also indicates that the freedom afforded by virtual representations to augment motor tasks beyond the restrictions of physical space makes them superior to real-world alternatives for learning in many cases. Several other advantages include the intuitive representation of spatial information in virtual environments, as well as their ability to represent motor tasks in a variety of contexts [3].

In clinical trials of 3 to 6 weeks, VR approaches have resulted in a generally positive effect on health outcomes in users [4]. As early as 2001, VR technologies have been in regular use in clinical environments for rehabilitating of a variety of motor impairments [5]. In 2002, VR applications were shown to improve fine motor control of the hand in the chronic phase following a stroke, indicating that the technology is useful in fine-grain and coarse-grain motor tasks [6]. In more recent VR implementations, like the Rehabilitation Gaming System by Cameirao et al. [7], functional improvements are attained from directly mapping body movements to first-person virtual avatar representations [8]. The motivational effects of these virtual systems are also well documented in recent findings [9]. Multimodality is often a primary component of VR environments, as they are intended to mimic and augment the multimodal feedback environment of real-world interactions with therapists and trainers [10].

Despite the many advantages presented in VR approaches for motor learning, they include some limitations as well [11]. One limitation is that, while there is a large volume of research supporting the usage of these systems for upper-extremity tasks, the same cannot be said for lower-extremity tasks, and so more work is needed to support lower-extremity applications for these systems [12]. VR systems are rarely used in home environments, due to high complexity, maintenance requirements and very high costs [13]. As an alternative, some augmented reality (AR) systems, where the real world is augmented with the presence of virtual objects and information, have been employed [14,15]. However, there is insufficient testing to promote AR-based approaches as effective mechanisms for home exercise. Furthermore, several robotic systems, which utilize mechanical joints or input mechanisms to support and guide motion tasks, have been developed. However, it is not clear whether these approaches are scalable or can be adopted for a wide range of motor tasks [16,17].

2.1.2 Serious games

In addition to VR technologies, serious games have recently gained traction in motor learning research as platforms for the abstraction and implementation of motor exercise programs. Serious games often provide motivating and interactive engagement with motor tasks despite their repetitive nature [10,18]. They have been indicated, for example, by Ma and Bechkoum [19], to yield short term improvements in motor impairment and generally positive health outcomes in the post-stroke rehabilitation process. Since motor tasks are abstracted into gameplay objectives, performance in gameplay can be linked to performance in the original motor task with proper design. An example of this mapping is the TheraDrive system [20] in which motor performance is abstracted in gameplay as the effectiveness of the user in completing various driving tasks [21]. Their effectiveness in long-term recovery has also been verified by Alankus et al. [22] in a case study with an individual several years into stroke recovery. Some other aspects of serious games that are specifically applicable to the motor learning domain include dynamic difficulty adaptation [23] and the prevention of compensatory motion in rehabilitation [24].

Research on the application of serious games toward motor learning has uncovered several important findings in recent years. The primary emphasis has been on the design elements of serious games that support the motor learning process, as they are a natural multimodal medium of abstraction for motor performance information. One of these findings is that the input-assessment-feedback cycle present in serious games allows for motivation and learning to complement one another with the introduction of novel learning objectives [25]. Furthermore, they provide a sense of progression in otherwise repetitive motion tasks through meaningful play [26] where correct actions yield positive and meaningful outcomes [27]. When designed under these considerations, serious games can maintain motivation and interest in the long-term usage of a variety of tasks [28].

From recent research on the adoption of serious games to motor learning and rehabilitation, several requirements have been delineated. Stroke rehabilitation research, in which the elderly population is primarily targeted, has been a leading field in deriving these design requirements [29-31]. One of the most important requirements for serious game design in motor learning is customizability, due to the significant variations in user proficiency, motor ability, sensitivity to various modalities, and trainer requirements and goals [32,33]. This can be achieved through person-centric design, where various aspects of the game adapt to individual players [34]. This adaptation should occur dynamically, including elements, such as real-time difficulty adjustment, that are based on increasing user proficiency [35,36]. To measure the effectiveness of a game's adaptation, Flow Theory [37] is often used, wherein the user's engagement is mapped as a relationship between user skill and game difficulty. These systems are also encouraged to elicit real-time problem solving in motor tasks by supporting meta-cognitive strategies, such as self-assessment, modeling, and thinking aloud [38], and assigning explicit and clear rewards for the successful completion of motion tasks while seamlessly correcting erroneous motion [39]. Serious games that are aware of a user's emotional state during gameplay can also implement real-time adaptation using this information [40].

2.2 Motion Sensing Mechanisms

For systems supporting motor learning, the choice of a motion sensing mechanism is often nontrivial. Research in this area has adopted several interfaces for receiving real-time motion data from individuals to allow systems to make assessments and provide feedback for motor learning. Since motor learning can occur in a variety of tasks and at varying levels of complexity, there is no single solution that has been adopted in this field for all exercises. Instead, the interface is often adapted to the motor tasks and the scope of the motor activity.

Among the various factors for deciding the type of interface are the region of motion, degrees of freedom, coarseness of motion, mapping between motion and game elements, and the detection and prevention of compensatory motion. Tanaka et al. [41] compared the performance and usability of several interfaces, measuring the effectiveness of each interface against these metrics. Commercially available devices commonly used include the Nintendo Wii remote, which contains an accelerometer, infrared sensor, gyroscope, vibrotactile motors, LED light signals, audio output, and input buttons—the combination of which make it an ideal device for haptic feedback and basic motion capture [42,43]—and the Microsoft Kinect, a depth-camera device capable of recording real-time body motion [44-47].

The Wii system was proposed as an exercise platform for motor learning in cerebral palsy therapy by Deutsch et al. [48] in 2008 and for stroke rehabilitation by Brosnan [49] in 2009, amongst many other options. However, the Wii remote is limited to a single point of tracking, and motion data provided by the accelerometers can sometimes be subject to inaccuracies [41]. The joint tracking mechanisms of the Kinect were found to be useful in determining progress and detecting compensatory motion. In a thesis study on the effectiveness of this device, LaBelle [45] indicated that it can be an effective method for motion capture when a single user is present, particularly when used in conjunction with the Wii Balance Board.

However, there remains the question of whether interfering factors could harm the accuracy of the

Kinect's capture data, since it is prone, as are all camera-based tracking devices, to interference caused by occlusion or the motion of other individuals, and it is limited in the range at which it can capture and track movement at the joint level. While Wii remote accelerometers provide the most cost-effective solution for input, the Xbox Kinect motion control can capture depth data with the highest detail, and is thus suitable for full-body motion. Other interfaces, such as the Wii Balance Board and PlayStation Move camera are considered, although the limitations on freedom of motion in each make them effective for only a specific range of exercises.

3. Modality Selection and Mapping

The three primary sensory channels used in motor learning systems are audio, visual, and haptic. In combination, these channels form the foundation for decades of multimodal systems within the rehabilitative space [50], and as indicated by Bongers and Smith [51] and Beursgens et al. [52], these systems are often adaptable to a variety of individual users. However, multimodality does not come without its drawbacks in motor learning. Sigrist et al. [53], for example, indicated in their study that multimodality is likely only limited in its advantages in cases in which the motor task is complex in nature. Qualities often attributed to the most effective forms of multimodal feedback in motor learning systems include accuracy, customizability, and measurability [54,55]. As Parker et al. [56] indicated, this feedback should also facilitate self-assessment by providing the Knowledge of Results (KR) and Knowledge of Performance (KP) in a frequent and explicit manner. The focus of recent work has been the mapping of modalities to various domains of motor performance information in a multimodal system. A detailed review by Sigrist et al. [57] indicates the best practices for implementations in each of these modalities, emphasizing the need for an approach to scale well with increasing motor task complexity as a user becomes increasingly proficient. Some of the many findings in this review can be summarized as give below.

3.1 Audio

Error sonification, or the augmentation of errors in motor performance, has been indicated as a highly effective practice for audio modality, when combined with other modalities and for specific motion attributes [58]. Audio signals can be used to convey several dimensions of information about an error, including when it occurs, in what direction the user must correct their motion, and the degree of error. As motor tasks are often repetitive in nature, the rhythmic nature of audio can be exploited to correct a user’s motion in the temporal domain [59]. It has been shown to combine well with haptic and visual feedback under these assumptions [53].

Several studies on the application of audio toward motor learning have reinforced its potential usage in a variety of motor tasks. Wallis et al. [60] implemented real-time motion sonification using music to impart movement in stroke rehabilitation tasks. Ronsse et al. [61] demonstrated that for the pacing and temporal coordination of hand movements during complex bimanual tasks, real-time audio feedback can outperform visual feedback in terms of skill retention. When asked to complete the task without feedback, participants who had received visual feedback retained less of the coordination learned in training than those with audio feedback. These and other findings suggest that if synchrony or rhythmic flow of motion are desirable outcomes or motor learning objectives, audio signals as feedback can facilitate learning under complex tasks.

3.2 Haptics

The same principles in audio feedback do not hold true for haptic feedback, where the performance of error augmentation can suffer as a motor task becomes increasingly complex [57]. Instead, the practice of adaptive haptic guidance, or the use of haptic signals to navigate a user through a motion task based on the user's skill level, has been suggested as a more scalable approach, so long as it is delivered on an as-needed basis [62]. It can be demonstrated that this implementation of haptic feedback does not lose effectiveness if the complexity of the signal matches the complexity of the motion task [63]. One example of such guidance is a haptic tunnel in which a user's motion can be considered correct in the 3D spatial domain [64].

Several usages of haptic guidance in practice have outlined its effectiveness as a form of spatial navigation through the motion trajectory of a motor task. Feygin et al. [65] demonstrated the effectiveness of the haptic guidance approach in the temporal domain by indicating its effect on the manual recall of a motion. Grindlay [66] presented an application of haptic guidance through musical motor learning by assessing recall in terms of note timing and loudness under a range of performance indicators, showing that haptic guidance resulted in reduced performance error.

3.3 Video

Visual modality is perhaps the most highly used of the three channels, due to the high degree of complexity with which information on motion can be represented in the visual space [67]. The observational data of a motion is often allocated to this channel in such a way that a user can have a visual reference by which to compare his or her motion to the ideal trajectory or posture [57]. Research on visual feedback has utilized the real-time projections of a user [68], a trainer/expert [69], and both simultaneously [70].

The concurrent, simultaneous projection approach has proven particularly effective as it can clearly indicate where a user's motion deviates from an expert's motion for a particular motion task [71]. Despite the complex capabilities of the visual domain, often the representation of feedback in this modality is kept relatively simple for complex motor tasks to prevent an overload of information [72]. In the domain of motor learning, often the visual domain is utilized as a means of providing the initial template of a motion activity to a user through demonstration and imitation. This process can be observed, for example, in the work of Jaume-i-Capo et al. [73], who utilized real-time Kinect body projection to improve user performance in motor tasks in terms of task completion time.

4. Multimodal Integration

Multimodal presentation is an issue of interest in motor learning research due to the complex nature of providing feedback across more than one modality. The key reasoning behind its use is that human interaction is multimodal in the real world [74,75], including interactions between an individual and trainer [76]. The order and pattern by which multimodal information should be integrated has long been the subject of study in the field of human-computer interactions [77-81]. To discuss the various ways by which multimodal feedback can be presented, the 2×2 classification of multimodal interfaces by Nigay and Coutaz [82] is used as a basis (Table 1).

Table 1. Multimodal classification according to Nigay and Coutaz [82]

Fusion style	Use of modalities	
	Sequential	Parallel
Integrated	Alternate	Synergistic
Non-Integrated	Exclusive	Current

Style 1: Alternate

This is the approach to delivering multimodal cues in which the modalities refer to the same information, but are delivered in sequential order. This is the equivalent of focusing all modalities on a single feedback domain but delivering them at various levels of granularity. For example, consider "pacing" or "temporal feedback" as a category. A system can, for instance, use rhythmic tones or music to guide the pace during an attempt [83], then use a haptic metronome [84] to guide pacing between attempts, and visually give terminal feedback on pacing at the end of a session in the form of a report or score [85]. In this manner, all modalities have been assigned to the same area of information on motor performance, but their delivery is ordered in different timing frequencies.

Advantages

- The primary advantage of this approach is that since individual users may have biases toward different modalities (including selective attention to some modalities over others) [86], focusing all of these modalities on a single category of information ensures that feedback on this information is delivered to the user in at least one modality in which the user is comfortable.
- Furthermore, since the information is delivered sequentially, any interfering effects that could happen in parallel transmission (when two modalities distract from one another) are avoided [87].

Disadvantages

- A disadvantage of this approach is since all modalities are focused toward one category of feedback, the user may miss valuable information in the other categories.
- Furthermore, if the user constantly needs to switch between modalities, cognitive overload may occur if the feedback cues are not carefully designed to complement one another [88].

Style 2: Exclusive

The exclusive delivery approach refers to the sequential delivery of multimodal cues where each modality is attributed to different information or tasks. This is achieved by assigning each modality to a feedback type but varying the frequencies at which feedback is delivered between the modalities. As an example, postural information could be delivered as a single report at the end of a motion exercise session, showing a dual-avatar replay or image [89] that visually indicates where the user's posture deviated from the target posture during the exercise session. An alternative version of this approach focuses on error-based feedback, giving only feedback in one category with one modality when a large error occurs in that domain.

Advantages

- This mode of interaction resembles the feedback process used during guided exercise with a trainer. Trainers will often provide feedback sequentially, focusing on correcting one aspect of an individual's motion at a time, but can switch between feedback domains as needed depending on the type of error made by an individual.
- The assignment of feedback categories to modalities allows individuals to categorize and efficiently process incoming information [57], allowing a range of information about motion to be processed simultaneously.

Disadvantages

- Intermodal lag in the sequential presentation of information [90] may cause significant delay issues for complex tasks, especially under numerous, rapid repetitions of a motor task.
- Using different granularities of feedback for different categories can have undesired effects on the relative amount of motor learning in each domain. For example, if an individual is receiving far more frequent feedback on progression than posture, postural performance may suffer due to the relative lack of feedback in that category.

Style 3: Synergistic

In the synergistic approach, cues from multiple modalities are delivered in parallel and all modalities are assigned to the same information or task. This approach involves choosing a specific category of feedback and presenting bimodal or trimodal feedback on that category in unison. In essence, all feedback interfaces are focused on providing the same information at the same time.

Advantages

- Synergistic error feedback is ideal for scenarios where all attention is oriented toward a single movement task. In these instances, it is shown to enhance accuracy [91].
- A phenomenon known as sensory enhancement or inter-sensory facilitation is known to occur in the process of synchronized multimodal information processing, which improves the rate and precision of information processing [92].

Disadvantages

- As in the alternate strategy, this strategy carries the same disadvantage of slowing the rate of learning due to the focus of information on a single domain of feedback at a time in each session.

Style 4: Concurrent

Finally, the concurrent approach delivers multiple modalities as parallel cues, but they are not linked together in meaning as in the synergistic approach. Feedback in each category is assigned to a single modality, and all information is presented in parallel.

Advantages

- This approach is based on the strategy posed by Sigrist et al. [57] for the concurrent multimodal presentation of information. The approach stems from the multiple resource theory [93] that suggests that humans can efficiently compartmentalize information processing across modalities, although not entirely without interference [94].
- Using this approach enables all relevant information for motor learning involving a motor task to be efficiently and simultaneously delivered to the user. Even in cases where attention and focus are selective, the concurrent approach ensures that all of the information is made available such that learning can occur in any or all domains.

Disadvantages

- There are valid concerns about cognitive overload occurring under this approach [95]. This is especially true due to the time-sensitive or pressure-inducing nature of motor exercise tasks, as the user is attempting to maintain a certain pace, complete a number of repetitions within a time limit, or reach a certain progress goal [96].
- Since information is being presented in parallel on three different aspects of a user's motion, selective attention toward one modality or domain may distract from learning in other domains.

5. Perceptual Bandwidth and Information Transfer

To determine how the effectiveness of modality usage can be evaluated in motor learning, it is important to observe perceptual bandwidth and information transfer in each modality. These measures have allowed researchers to quantify the effectiveness of a particular modality in delivering feedback on motor performance in a particular learning domain (spatial, temporal). These measures can therefore be used to assess how well a system facilitates motor learning in each modality.

5.1 Perceptual Bandwidth

In this context, perceptual bandwidth is the maximum *quantity* or *rate* of information that can be perceived within a modality and time period. For simplicity, the *rate* of transfer was used for comparing modalities.

- Estimates on the bandwidth for vision depend on how far along the cognitive process the information has travelled, but at the optic nerve, recent estimates place it at approximately 3×10^6 bits/sec [97].
- For haptic stimuli, the estimate is highly subject to the type of haptic stimulus and the surface dimensions of reception, but it is typically estimated at 100 bits/sec [98].
- For audio stimuli, the bandwidth of the ear can be estimated at around 10,000 bits/sec [99].

These estimations are misleading to an extent, as they model stimulus-response as an isolated event. In the realm of touch, for example, we can use more than just a fingertip to interact with the world. In addition to isolated touch events, there are haptic sensations that we can feel across the surface of our skin to experience a rich language of information. As an example, haptic displays allow us to perceive a complex graphical representation using our hand or arm as a surface [100]. Furthermore, we can perceive temperature, vibrations, and pain in addition to pressure on our skin. Hence, it is useful when comparing the three modalities to appreciate the complex 'dimensionality' that can be expressed with stimuli in each modality. For example, some commonly used dimensions of information in the visual modality include depth, distance, direction, color, size, texture, and shape, among others. However, a significant amount of this information can be conveyed in the audio and haptic modalities as well [101,102].

5.2 Information Transfer

When conveying information in multiple modalities, one powerful measure to evaluate the effectiveness of design in each modality is information transfer (IT), which measures the efficiency of transfer of information by pairing stimuli and their corresponding responses together. The formula [103] for IT is as follows:

$$IT = \sum_{j=1}^{K} \sum_{i=1}^{K} P\left(S_i, R_j\right) \log_2 \left(\frac{P(S_i|R_j)}{P(S_i)}\right) \quad (1)$$

In this equation, S_i and R_j are a paired stimulus and response while K denotes the number of variations of stimuli and responses prepared for the experiment. The equation computes the average amount of information transfers over the entire set of these variations weighted by the joint probability $P\left(S_i, R_j\right)$ of each pair, and is expressed in bits. $P\left(S_i \middle| R_j\right)$ denotes the conditional probability of S_i given R_j. Other measures for determining effectiveness in each modality have utilized percent-correct scores, questionnaire results, and other error rate measures, but were less accurate in determining communication efficiency for absolute identification tasks [103,104].

The structure of a study on IT will typically develop K different stimuli and K different responses in a one-to-one correspondence, and present a subject with randomly selected stimuli from the set, noting their response by accumulating a stimulus/response confusion matrix. One can then derive a maximum likelihood estimate for IT using the values of the confusion matrix as follows:

$$IT_{est} = \sum_{j=1}^{K} \sum_{i=1}^{K} \left(\frac{n_{ij}}{n}\right) \log_2 \left(\frac{n_{ij} n}{n_i n_j}\right) \quad (2)$$

where, n is the total number of trials, n_{ij} is the number of times the stimulus-response $\left(S_i, R_j\right)$ is noted, and the row and column sums n_i and n_j are the totals $n_i = \sum_{j=1}^{K} n_{ij}$ and $n_j = \sum_{i=1}^{K} n_{ij}$. Since we are measuring in bits, we can note that the maximum amount of transfers is equivalent to the expressive capability of the number of bits used: 1 bit can express a maximum of two different pieces of information, while 4 bits can express 16, etc. In general, this can be expressed as $IT_{max} = \log_2 K$. One can compare the values IT_{est} and IT_{max} to determine how well the current modality design facilitates the transfer of information. When the temporal dimension is involved, such as when continuously delivering a series of stimuli, IT can be expressed as the rate IT_{rate} in bits/sec. Finally, it is possible to derive the number of alternatives K' by using the reverse of the IT_{max} equation with the calculated IT_{est} as: $K' = 2^{IT_{est}}$.

One restriction with using IT measures in motor learning is that the measure was developed for use in absolute identification (AI) tasks where a response should correspond exactly with a stimulus to form a match. For example, Alluisi et al. [105] examined the response given either verbally or through the press of a key when a subject is presented with an Arabic numeral illuminated on a display, while Tan et al. [106] used multi-finger tactual stimulation and had subjects recognize patterns based on varying frequency and amplitude. To accurately assess IT in more complex multimodal systems, careful consideration should be taken in designing motor tasks for evaluation in such a way that this type of identification is possible in each modality.

6. Conclusions

In this paper, popular approaches over the last few decades for the design, implementation, and integration of multimodal feedback have been explored in the domain of motor learning with an emphasis on rehabilitation. Findings in the literature indicate that considerations of the motor task, including context, motor regions, complexity, spatial and temporal variation, and considerations of the learner, including proficiency and cognitive load, should all be incorporated in the design of the most effective approach in any scenario. While rehabilitation was the primary focus of this survey, the principles covered here can be applied to a limited extent to other application areas of motor learning, including athletic training, so long as careful consideration is paid to the restrictions and limitations placed on each approach by these application domains.

One of the primary challenges currently being explored in this field is the modulation of multimodal feedback as learning proficiency improves in a motor task. Specifically, the rate at which feedback should be faded in each modality based on motor task complexity is of interest, particularly when modalities are integrated to provide feedback. Furthermore, as there is no universally accepted standard for motor performance assessment, one remaining challenge is to develop a framework for the independent assessment of motor performance data in the spatial and temporal dimension in such a way that a system can account for both user variation and task variation.

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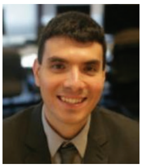

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