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Haptics-mediated approaches for enhancing sustained attention: framework and challenges

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Abstract Sustained attention is essential in the daily human activities of perception, manipulation, and locomotion. An improvement in sustained attention exhibits potential impacts in several scenarios, including the treatment of mental disorders, such as the attention-deficit/hyperactivity disorder, and the training of certain professionals, such as aircraft pilots, who work under environments with heavy cognitive loads. In this study, we review the haptics-mediated sustained attention-training approaches from the afferent and efferent perspectives based on the bidirectional information flow in the haptic channel. Subsequently, the feasibility of modulating and enhancing attention via the haptic channel is analyzed based on the studies that have investigated the correlation between attention and the afferent/efferent pathways of the haptic channel. We identify several research questions, including how to design diverse haptic training tasks via the afferent and/or efferent pathways and which adaptive strategies can be used to adjust the difficulty levels of haptic training tasks to ensure user engagement. Furthermore, we examine the behavioral and biological evidence that can be used to validate the training efficacy, the manner in which the neural mechanisms underlying the attention-enhancing process can be understood, and the effective variables that can be attributed to the near- and far-transfer effects. In addition, we discuss the difficulties associated with the development of novel haptic technologies. In this study, we intend to investigate the potential impact of haptic stimuli on neuroplasticity and to promote the study of haptics-mediated sustained attention training.

Keywords sustained attention, attention enhancement, haptic interaction, robotics, electroencephalogram, virtual reality, human-computer interaction

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1 Introduction

Attention is the foundation of human neural and cognitive activities, and effective attentional control forms the foundation of perceiving external information and motion control [1]. Attentional control refers to an individual's capacity to select the things that they devote attention to and the things that they ignore. In lay terms, attentional control can be considered to be the concentration ability of an individual or a type of mental control [2]. In this section, we introduce the concept of sustained attention, discuss the potential impact of attention training, and introduce the existing non-haptic approaches for conducting attention training.

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1.1 Sustained attention

Sustained attention refers to the ability of an individual to continuously maintain their focus on a particular task and is considered to be the fundamental dimension of attentional control [1, 3–5]. Effective sustained attention involves the activation of the three attention network components defined by Posner et al. [3], i.e., alerting, orienting, and executive control [6]. The alerting system is considered to ensure the maintenance and achievement of an alert state, whereas the orienting system is considered to ensure the selection of suitable information based on the sensory input. Further, executive control solves the conflicts among various responses.

This study reviews the state of the art in attention training, including the haptics-mediated approaches, and explores whether the attentional control skills can be enhanced by training tasks using the human haptic channel. This study is instrumental to better understand the haptics-mediated approaches for sustained attention training.

1.2 Potential impact of attention training

Attentional control ability considerably impacts the quality of our life, and a considerable amount of our daily behavior relies on the maintenance of sustained attention over time, such as taking an examination, driving a car, or writing a letter [5]. The learning abilities, social skills, and happiness of humans are closely related with their ability to control their attentional focus [7]. Decreased attentional control can result in mental disorders, including attention deficit disorder (ADD) and attention-deficit/hyperactivity disorder (ADHD), which may prevent individuals from learning and working in an efficient manner [3].

Attentional control ability can be improved by attention training [8], and an attention-training study can have a beneficial impact on certain populations. Attention-training studies can present new methods for the diagnosis, prevention, and treatment of various mental disorders or neurological diseases. One relevant group considered in this study includes ADD and ADHD patients, whose main symptoms include frequent involuntary distraction and an inability to voluntarily control where and when to pay attention [8]. Further, elderly people with declining cognitive function, such as mild cognitive impairment (MCI), can benefit from attention training to improve the quality of their daily lives [9]. Furthermore, attention deficits are common after brain injuries, such as traumatic brain injury (TBI) and strokes, and significantly impact the academic, vocational, and social outcomes of patients [10, 11]. Neuroplasticity is critical during the recovery stages after the occurrence of brain damage [12], and effective and timely attention training can substantially benefit the patients [11].

Another contribution of attention-training studies is that they may lead to novel approaches for training professionals under heavy workloads, high-pressure, and fast-paced situations, such as simultaneous interpreter, pilots, and air traffic controllers [13]. These professionals must maintain a high degree of sustained attention for a long period of time during the execution of a task and must be able to provide quick and accurate responses under a high cognitive load [14, 15]. For example, aerial combat requires the intense concentration of pilots to quickly process large amounts of information and make accurate decisions to ensure the completion of the combat mission and the safety of the flight crew. In addition, drivers often require high sustained attentional control to continually scan the road and the surrounding conditions while driving [16]. Distraction for even a brief moment in any of the aforementioned professions can result in disastrous consequences.

Attention training can benefit healthy individuals because the ability to focus attention affects the learning efficiency and work quality and can enhance the well-being. For example, the ability to devote attention in school plays an important role in the learning ability of children [8]. Diamond et al. [17] demonstrated that attention training can improve the cognitive control abilities of students in pre-school and that this is strongly correlated with their academic achievement. Attention training in children has also been demonstrated to be effective in facilitating learning and improving the cognition, emotion, and performance [18, 19].

Currently, mental distraction and multitasking are nearly ubiquitous. According to previous study [7], individuals experience involuntary distractions and remain in a mind-wandering state more than 50% of the time. Mind-wandering is one of the causes of unhappiness; thus, attention training can help healthy individuals to promote engagement by reducing involuntary mind-wandering [20, 21].

The study of attention training can contribute to the fundamental research in the field of cognitive neuroscience. Attention forms the cornerstone of human cognitive abilities; therefore, the attention training studies can aid in achieving a multilevel and integrated understanding of the neural mechanism of attention as well as the related brain structures and functional connectivity[1]. Longitudinal studies on attention training can increase the knowledge of the process, pathways, and mechanism of neural plasticity, which refers to the structural and functional changes in neuronal circuits in response to experience [22].

1.3 Non-haptic attention-training approaches

Before presenting the literature related to haptics-mediated attention training, we introduce the existing non-haptic attention training approaches, which can offer knowledge for understanding the underlying neural mechanisms of modulating/training attention. In the field of cognitive neuroscience, the typical approaches that aim to train attention include meditation, action video games, cognitive training games, and neurofeedback.

Meditation practices have been investigated to improve the mental abilities of individuals by improving attention and reducing stress. There are various forms of meditation practices, including mindfulness meditation, integrative body-mind training, yoga, and exposure to nature [8, 23–28]. Several studies have demonstrated the efficacy of meditation training for improving attention [25, 29]. The advantage of using meditation to train and regulate attention appears to be based on its generalization ability; therefore, the training effects can be transferred to various types of cognitive activities [8]. However, because a meditation training cycle generally requires several months to years [30], it is challenging to motivate the trainees to retain interest in the training procedure for such a long period of time.

Recently, action video games have become an appealing tool to probe the possibilities of improvements in the neuroplasticity of individuals with respect to their perception, attention, and cognition [31]. Studies related to action video games have provided new insights on how to foster learning and neuroplasticity across a wide variety of tasks and domains [32]. Previous studies have also demonstrated that extensively playing video games may enhance the visual attention and executive control [33,34]. For example, playing action video games can enhance the capacity of the visual attentional system, alter the visual selective attention [35], and improve the reading ability of the dyslexic children [36]. In addition, Anguera et al. [9] demonstrated that a custom-designed video game can enhance the cognitive control abilities of elderly people. Although many studies have reported the positive effects of video games on attention, it is unclear whether the training effect is task-specific or whether it can be generalized to untrained tasks.

In contrast to the action video games, cognitive training games are designed to improve the cognitive abilities of the trainees by repeatedly performing the cognitive tasks embedded in the games [37]. These games expose the users' brains to increasingly difficult training in accordance with the game difficulty levels by providing personalized training programs for the users to train their attention and/or memory based on various computer-based exercises[2][3] or the virtual reality (VR) technology [38,39][4]. The games also challenge the users by providing a controllable environment in which the cognitive challenges can be presented with precise delivery and control of distracting auditory and/or visual stimuli.

Neurofeedback is another viable option for clinical intervention in the treatment of ADD and ADHD [40, 41]. In neurofeedback training, a desired brain state can be achieved through associative learning, and the association between the desired state and reinforced feedback stimulus is learned by the trainees [42, 43]. Further, the electroencephalograph (EEG) neurofeedback [44, 45] and functional magnetic resonance imaging (fMRI) neurofeedback [46, 47] have been examined for training sustained attention.

In the clinical field, the hierarchical model of attention process training (APT) has been extensively used for evaluating the attention of patients exhibiting various neurologic pathologies [10, 48–50]. Studies

1) www.humanbrainproject.eu.
2) http://www.lumosity.com/.
3) https://en.wikipedia.org/wiki/Schulte_table.
4) http://narbis.com/product/.

on patients with stable acquired brain injuries have demonstrated that APT considerably influences the performance of executive attention tasks [12]. APT has also been found to be an effective methodology for improving attention deficits after incident strokes [51] and acquired brain injuries [11]. Other methods, including brainwave entrainment (BWE) [52], the brain-computer interface (BCI) [53, 54], brain stimulations, such as repetitive transcranial magnetic stimulation (rTMS) [55], and transcranial direct current stimulation (tDCS) [56], have also been studied to promote attention.

The majority of the aforementioned attention-training methods primarily rely on visual and/or auditory signals, and relatively few systematic studies have been conducted that use haptic tasks for conducting attention training. For example, the design principle of video games is to attract user's attention by presenting vivid animation, stunning audio effects, and interesting stories, which are primarily mediated through visual and audio channels [31]. Because of the similarity of the neural signal transduction process between the visual, audio, and haptic channels, exploring whether attentional control skills can be improved through haptic tasks is a promising topic. In addition, it is important to determine whether the tasks performed based on a combination of haptic, visual, and auditory channels can produce a better outcome in attentional training when compared with that obtained by the tasks performed using individual channels.

Neurofeedback training approaches can be augmented by introducing the haptic channel. Current neurofeedback primarily uses visual or auditory signals as the reward to achieve a conditional feedback effect. However, it is unclear whether haptic signals can be used as the reward and whether there would be a significant added benefit based on the introduction of the haptic channel.

With the advent of new haptic technologies in the previous two decades, many commercial force and tactile feedback devices have been developed[5)]. These devices and the related haptic rendering technologies can be used to examine additional methods for utilizing the haptic channel to enhance the attentional control. The investigation of whether intensive activation/utilization of the haptic channel produces significant attention-training effects would be an interesting research topic.

The remainder of this study is organized as follows. In Section 2, we introduce a framework for classifying the existing haptics-mediated training tasks. In Sections 3 and 4, we discuss the haptics-mediated attention-training studies in the case of afferent and efferent pathways. Further, in Section 5, we discuss future research topics and challenges associated with haptics-mediated training, and we present the conclusion of this study in Section 6.

2 Classification framework of the existing haptics-mediated training tasks

To investigate previous studies related to the haptics-mediated attention training tasks, we propose a framework in this section for classifying the existing training tasks based on the bilateral information flow feature of the human haptic channel. Further, the uniqueness of the human haptic channel is summarized and compared with the visual and auditory channels. The framework for formalizing a detailed review is subsequently introduced in Sections 3 and 4.

2.1 Unique features of the haptic channel

The potential of the haptics-mediated attention training can be determined by evaluating the unique features of the haptic channel compared with other sensory channels.

One unique feature of the haptic channel is its sensory capacity. Haptic receptors are extensively distributed in the skin, ensuring the reception of haptic stimuli over the entire surface of the body. Further, the environmental changes can be perceived using the mechanoreceptors in the skin, and perception can simultaneously occur at several sites on the body. In addition to the skin, several other receptors in the human body, such as the kinesthetic mechanoreceptors in the tendons and joints, are responsible for force/motion perception [57]. This large sensory capacity can provide diverse methodologies for modulating the attention of the brain through the haptic stimuli imposed at multiple body sites.

5) http://www.worldhaptics.org/companies.

Another unique feature of the haptic channel is the bilateral information flow between the human brain and external environment during the performance of haptic interaction tasks [58]. With visual and/or auditory channels, the human brain can only receive the afferent information. In contrast, through the haptic channel, humans can actively output motion/force and simultaneously receive the afferent information from the mechanoreceptors [58]. The ability to output an accurate force and/or motion into the external physical environment is a unique feature of the haptic channel [57]. In terms of the mental workload, one hypothesis states that active force/motion output via the haptic channel may require stronger attentional resources of the brain (endogenous attention) when compared with the passively received information via visual or auditory channel (exogenous attention). Therefore, training tasks using the haptic channel may lead to more effective attention-training outcomes when compared with the tasks that used visual or auditory channel.

An additional unique feature of the haptic channel is based on the evidence obtained from biological evolution [59]. During the very early stage of an embryo, both the epidermis and the nervous system originate from the ectoderm [60]. The close connection between the skin and the nervous system suggests that it is worthwhile to study the modulating effect of haptic stimulation on the cognitive abilities. However, it is still unclear whether it is easier to invoke brain activity through haptic stimuli or visual or auditory stimuli.

Van Erp et al. [61] reported promising results based on touch- or haptics-mediated BCIs. They suggested that vibrotactile feedback can be felt more naturally when compared with the visual feedback and that vibrotactile stimuli lead to increased brain response. Meng et al. [62] demonstrated that tactile warning signals can elicit faster reactions from drivers in response to potential collisions than the comparable visual or auditory warning signals. In addition, Locher [63] observed that haptic training can improve the attentional control abilities of children. Young et al. [64] reported that the use of haptic spatial cues to reorient the visual spatial attention of people was natural and intuitive. Their results demonstrated a significantly decreased response time when both haptic and visual spatial cues were presented. Halperin et al. [65] conducted experiments on children with ADHD using motor control training games, such as games involving balls, hopping, and jump ropes, and the results demonstrated a significant improvement in ADHD severity from pre- to post-treatment. The aforementioned studies indicate that the haptic channel can produce similar, if not stronger, long-lasting effects on neuroplasticity with respect to the visual and auditory channels [66].

Privacy is another unique feature of the haptic channel. To use visual or auditory channel for attention training, an isolated and quiet room is usually required for preventing external disturbances. However, in haptics-mediated training tasks, trainees can receive the haptic stimuli applied directly to their bodies without any requirements on the external environment. This feature offers the potential for the application of haptic training in ubiquitous environments such as the subway. For example, Meng et al. [62] suggested that tactile warnings are less intrusive and bothersome when compared with the visual or auditory warnings. In their study, tactile warnings were directly delivered to the driver's bodies without a requirement to alert the remaining occupants of the vehicle.

2.2 Framework for classifying the haptics-mediated attention-training tasks

To methodically investigate the existing studies on the haptics-mediated attention-training approaches, we propose a simple classification framework according to the unique feature of bidirectional information flow of a haptic channel, as illustrated in Figure 1. This framework includes two main categories of training tasks that either use an afferent pathway or an efferent pathway.

In the afferent pathway category, trainees generally attend to and perceive the haptic stimuli transmitted through tactile and/or proprioception mechanoreceptors. This type of training task can be further classified into passive and active haptic perception tasks. In the former, trainees normally sit or stand still and attend to the haptic stimuli applied to the skin. The detection and discrimination of vibration stimuli are typical examples of passive haptic perception tasks. In contrast, an active haptic perception task involves the perception of haptic stimuli through active exploration [67, 68]. This requires hand

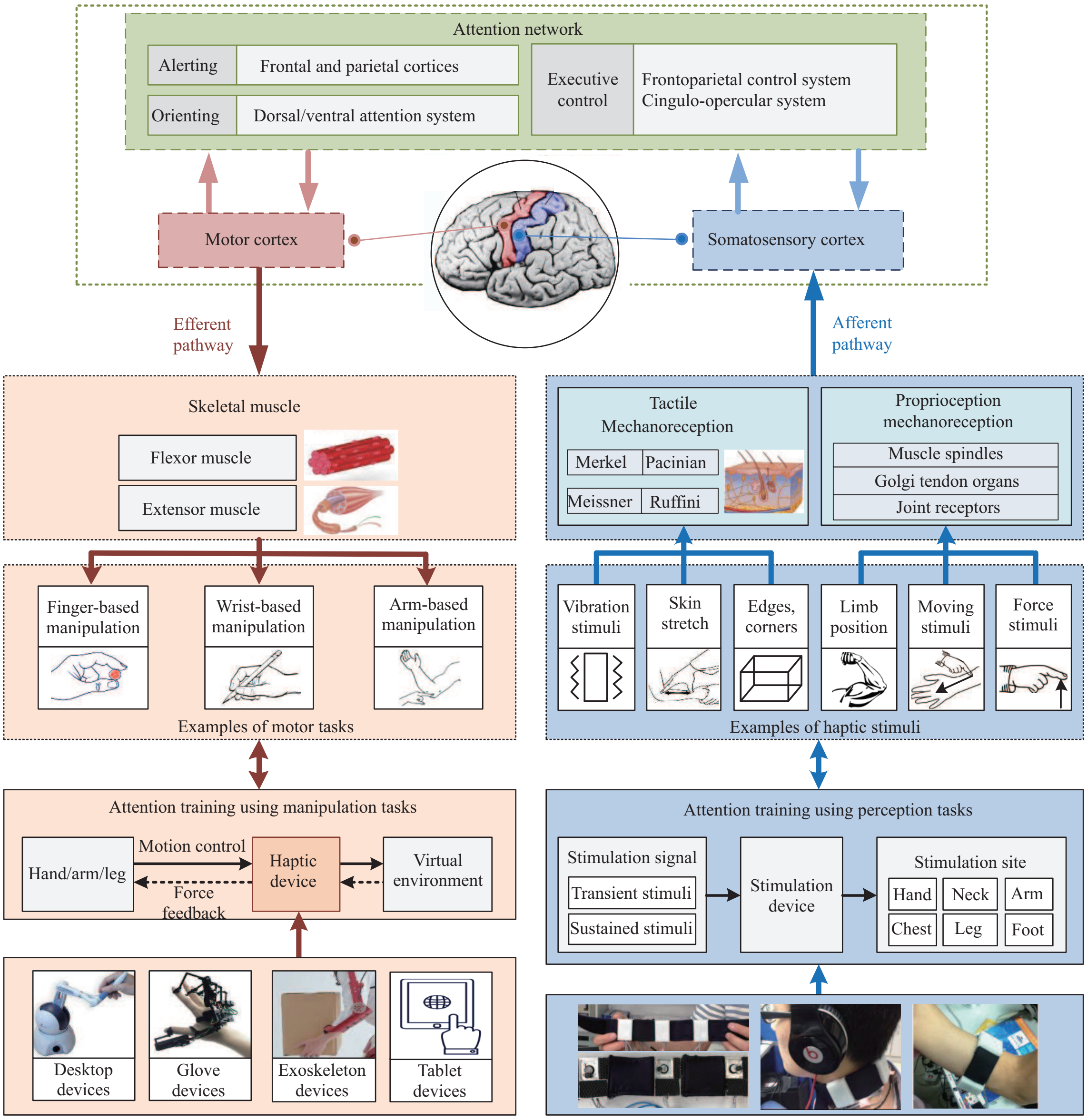


Figure 1 (Color online) A framework for classifying the haptics-mediated attention-training tasks inspired by the bilateral information flow feature of the human haptic channel.

or body movement and real-time modulation of the limb position and/or contact force against a target object. Edge and texture discrimination are examples of active perception tasks. It should be noted that an efferent pathway is involved in active haptic perception tasks because body motion is required in the active exploration process for touching an external object. However, we classify these tasks to belong to the afferent pathway category because the main objective of these tasks is to perceive and identify/discriminate the physical properties of the external environment.

In the efferent pathway category, skeletal muscles, such as flexor and extensor muscles, are considered to produce delicate motion for the output force. The tasks in this category include finger movement, wrist movement, arm movement, and so on. For example, as illustrated in Figure 1, the wrist-movement-based tasks can be designed using typical stylus-type haptic devices such as the Phantom Omni device [69]. While using such desktop devices, users hold a pen-like stylus. Dexterous manipulation tasks, such as precise sculpting or cutting along a predefined trajectory in the predefined force tolerance range, can be designed. In addition, bimanual coordinating tasks that require precise collaboration of the motion trajectories or force profiles between two hands can be designed. While performing these force or motion control tasks, the attention levels of users can be aroused by engaging in the production of a precise trajectory or force along with delicate muscle control. It should be noted that the afferent pathway is also involved in these force and motion control tasks because sensory feedback is required to rectify the motion error for precisely manipulating an external object. However, because the main objective of these tasks is to output motion and energy for manipulating the external objects, we classify these tasks into the efferent pathway category.

3 The potential of attention training via afferent pathway

In this section, we summarize previous studies that have investigated the influence of the haptic perception tasks on attention. In addition, we examine the neuronal activities during various haptic perception tasks, in particular, the activities relevant to the attention-related brain regions. These studies provide a foundation for understanding the impact of haptic perception tasks on attention modulation and demonstrate various possibilities for conducting perception-based attention-training tasks.

3.1 Effect of passive haptic perception tasks on attention

For several decades, brain wave synchronization and entrainment using rhythmic visual and auditory stimuli has been used for modulating and enhancing the attention of patients with mental disorders such as ADD and ADHD [52, 70–72]. The underlying mechanism of this approach can be attributed to the frequency-following effect in which the energy of a target frequency band of the EEG signal can be enhanced by sustained visual and/or auditory stimuli having a specified frequency.

The frequency-following effect also exists in the haptic channel. Sustained sinusoidal stimuli with a given vibration frequency has been demonstrated to be capable of provoking sustained attention [57]. Steady-state somatosensory evoked potential (SSSEP) is a BCI paradigm in which the brain response to the tactile stimulation of a specific frequency or amplitude is used [73, 74]. More specifically, the vibration with a specified frequency that is applied to the fingers and palmar surface can induce the response of the steady-state scalp-evoked potentials with the same frequency [75]. When a vibrotactile stimulation is repetitively applied to the finger, dense multichannel recordings of a scalp EEG with the same frequency are obtained in the vicinity of the primary somatosensory cortex [76].

Based on the frequency-following effect, attentional control can be trained using sustained vibrotactile stimuli. Wang et al. [77] observed the impact of sustained vibration on human EEG and proposed an attention-modulating approach based on a passive vibration perception task. In their experiment, a 15-Hz sinusoidal continuous vibration was applied to the users' hands through a haptic device. After a haptic stimulation session of 15 min, the sensory motor rhythm (SMR) energy value in the C3/C4 region of the brain was observed to be higher than the baseline value observed before stimulation. This result demonstrates the effectiveness of the modulation of the EEG activity using sustained vibrotactile stimuli [77, 78]. More importantly, the test of variables of attention (TOVA), a common attention-testing task, was performed before and after the stimulation session. As illustrated in Figure 2, the TOVA results indicate an improvement in the attention of the participants who received the stimulation when compared with the control group that did not. Thus, this study demonstrates the feasibility of the usage of sustained vibrotactile stimuli to enhance short-term attention. Longitudinal studies using multiple stimulation sessions are required to further evaluate whether vibrotactile stimuli can lead to long-term enhancement of the attentional control.

The beneficial effect of attention enhancement through the modulation of the SMR energy values discussed above can be explained by the role of SMR in the brain cortex. Increasing the SMR band power results in the reduction of the somatosensory and motor interference in basal thalamocortical circuits [79]. According to the attentional resource model, attention can be considered to be a limited-capacity resource [80], and this limitation influences the performance of selecting and attending to relevant information in the environment. SMR modulation has been found to be an effective neurofeedback

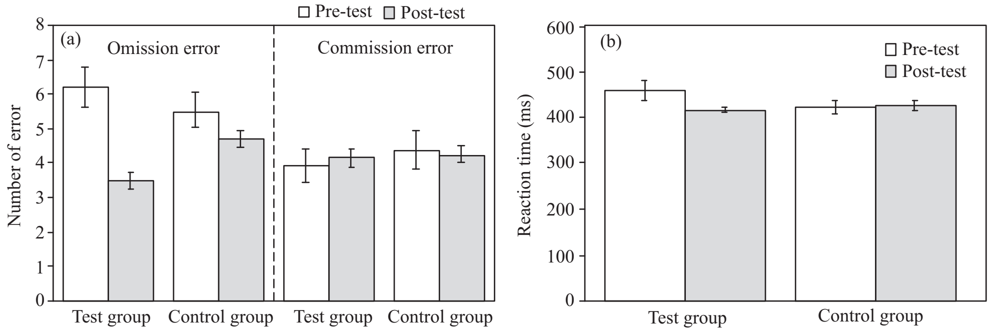


Figure 2 Performance of the TOVA tests in pre-test and post-test stage. Performance is measured based on the omission error, commission error, and reaction time. (a) Average number of errors, where the left-hand side indicates the omission error and the right-hand side indicates the commission error. (b) Average reaction time (ms).

training approach for enhancing the performance of the athletes [81]. This observation suggests that increasing the SMR may be an effective methodology for improving the attention-related performance.

There are several key parameters, such as the type of stimuli, the body site, and the spatiotemporal pattern of the haptic stimuli, associated with the design of passive haptic perception tasks. These parameters provide several options for designing the attention-training tasks using the passive perception paradigm. In terms of the type of stimuli, recent advances in haptic device technology offer numerous possibilities, such as vibrotactile stimuli [82], pressure, tapping [83], skin-stretch [84], and thermal stimuli [85]. Because the existing attention-related studies primarily involve vibrotactile stimuli, there are opportunities to explore the effect of other types of haptic stimuli with respect to the passive haptic perception tasks.

With respect to the body site, the large skin area provides abundant options for receiving stimuli. In addition to providing haptic stimuli to the hand, it is possible to mount vibrating actuators on different body sites such as the arm, neck, waist, and leg. Salzer et al. [86] developed a vibrotactile version of the attention network test (ANT) using the Simon paradigm. The participants wore a waist belt in which two vibrotactile stimulators were mounted on the right and left sides of the spinal column. Their experimental results demonstrated that the system was effective for measuring the three components of the attention network, i.e., the alerting, orienting, and executive control networks. Because this test involves intensive attention workload, it can be used as a training task, and multiple training sessions can be performed to validate its effect on improving the attentional control.

In terms of the spatial pattern of the haptic stimuli, single or multiple body sites can be used. To develop passive perception tasks using haptic stimuli from different body sites, it is important to understand the characteristics of haptic spatial attention. Previous studies on haptics-related spatial attention can provide useful guidelines for designing the perception-based attention-training tasks. Spence and Gallace reviewed the evidence that demonstrated that attention can be directed to the tactile modality or to a region, where tactile stimuli are presented in either an endogenous or exogenous (top-down or bottom-up) manner [87]. This result implies that tactile stimuli can be used to train endogenous or exogenous attention. For haptic stimuli on multiple body sites, the spatial pattern can consist of sequential or simultaneous vibrations. It is possible to place multiple actuators on the body and study the effect of using sequential or simultaneous vibrations on attention modulation.

In terms of the temporal pattern of the haptic stimuli, there are many options, including a sinusoidal wave, square wave, and pulsed vibration. Most of the existing haptic feedback devices are designed to use alerts or warnings to capture the attention of a user [88]. However, this can be disruptive when the user needs to focus on another task of higher importance. To explore whether haptic feedback can elicit a positive affect by managing the capture of attention across a wide spectrum, they evaluated six parameters that can impact the affective response for better management of user attention: stimulus location on the body, actuation type, actuation intensity, actuation profile, actuator material, and actuator geometry [88]. The results obtained from 30 participants indicated that the actuation profile most significantly impacted the affect. They also determined that the devices with a negative affect were better able to capture a user's attention. The results of this study can guide designers in modifying the key parameters of haptic devices to appropriately manage the attention of users and design effective attention-modulating/training tasks using haptic stimuli.

Lakatos et al. [89] explored the time required to detect the presence of the tactile stimulus as a function of its distance from the location on the body on which attention was initially directed. Their results indicated that the subjects required more than 200 ms to shift their attention from the right wrist to the left wrist. These observations indicate that some parameters, such as the spatial separation of stimulation sites as well as the inter-stimulus intervals, must be carefully determined while designing attention-training tasks.

Another promising topic is to explore the effect of multisensory perception tasks that integrate haptic and visual/auditory stimuli. Spence and Ho [90] reported that multisensory displays can capture driver attention significantly more effectively when compared with their unimodal counterparts (i.e., vibrotactile displays) and can be used to transmit information more efficiently and reduce the driver workload. Some researchers have claimed that vibrotactile cues are intuitive [91] and offer a particularly effective methodology for presenting directional signals to drivers. Based on these results, various multisensory training tasks can be developed and compared to investigate their effectiveness and differences.

3.2 Effect of the active haptic perception tasks on attention

Neuronal activity was observed in several previous studies when users performed active haptic perception tasks involving intensive attention. The results of these studies indicated that the attention-related brain activities differ between discrimination and detection tasks.

In discrimination tasks, stimuli must be processed more deeply than in the detection tasks. Additionally, stimulus-response mapping is relatively complex because each trial can require either a predefined response (i.e., the go stimulus) or the withholding of this response (i.e., the no-go stimulus) [92]. For example, in the classic sustained attention to response task (SART), users are required to withhold clicking a button when a target number (e.g., number 3) appears and to click a button when other numbers appear [93]. By providing haptic stimuli to the body sites such as the fingertip, similar SART tasks can be designed. Versatile paradigms can be proposed to differentiate the target cue and control cue. The possible options include a weak or strong vibration magnitude, a pulsed or continuous vibration, and spatial cues that can occur on either the left or right index fingertip. Based on the characteristics of the discrimination tasks, these haptic perception tasks may be helpful for enhancing the orienting and executive control components of the attention network [94].

In contrast to the discrimination tasks, detection tasks are more repetitive and less arousing. Thus, this cognitive simplicity increases the demand for endogenous control and maintenance of vigilant attention. Based on the characteristics of the detection tasks, these perception tasks may be helpful for enhancing the alerting component of the attention network [94]. When compared with the discrimination tasks, detection tasks produce stronger activation in attention-related brain networks, including the right dorsolateral and medial prefrontal cortex (PFC), right postcentral gyrus, and left posterior ventrolateral PFC [92]. These brain regions have been demonstrated to have a close relation with attention [94]. The aforementioned differences between the discrimination and detection tasks provide useful guidelines for the design of various perception-based attention-training tasks.

Attentional blink reflects the temporal costs in the allocation of selective attention. It is normally measured using rapid serial visual presentation tasks in which the participants often fail to detect a second salient target occurring in succession if it is presented between 180 and 450 ms after the first target. The existing studies on attentional blink mainly use visual and auditory stimuli [93, 95]. By replacing the targets with haptic cues, including vibrotactile cues, the haptics-based attention blink tasks can be developed for attention testing, modulating, and training.

3.3 The potential of attention training via afferent pathway

Because the active perception tasks require a close coordination between perception and motor control processes, they may lead to a higher mental workload than the passive perception tasks. This increased workload is likely to lead to a strong effect on attention training. In the future, systematic studies should be conducted to compare the effects of the active and passive perception tasks.

Several open research topics can be identified by examining the studies conducted on the correlations between the attention and perception tasks. In most of the existing studies, the participants sit in a relaxed manner, attend to haptic stimuli, and perform detection or discrimination tasks. There is no body movement during the perception tasks, which can be referred to as the passive perception mode. The human haptic channel is extensively used in the active perception tasks involving body movement [67,68]. For example, to perceive the texture of an object's surface, individuals must slide their fingers along the surface. To the best of our knowledge, no study has been conducted to explore the effect of active perception tasks on attention regulation and training. Because there are many features that can be actively perceived through the haptic channel, including shapes (e.g., edges, corners, curvature), surface properties (e.g., stiffness, roughness, texture), and forces (e.g., force magnitude, force direction), several studies can be conducted to compare the effects of various perception tasks on attention training.

In addition, most of the existing studies focus on the observation of neural activities during haptic perception tasks [96–98], and several studies have examined the feasibility of modulating attention using a specific type of passive perception task (e.g., perceiving sustained vibrotactile stimuli) [99]. A longitudinal study is required to validate whether attentional control can be improved after several days or weeks of training using haptic perception tasks. In addition to the behavioral evidence of attention enhancement, biological evidence is also required for identifying the plastic change in the attention network during and after the training sessions.

Finally, to explore potential methods for using multisensory stimuli for attention training, one can explore whether the integration of visual and tactile stimuli results in better performance when compared with those of the individual presentations in either modality alone (i.e., whether the additional sensory recruitment can improve the training outcome). Spence et al. [100] investigated the cross-modal links between vision and touch while converting endogenous spatial attention. When the participants were told that the visual and tactile targets were more likely to be on one side than another, the discrimination responses for the targets in both modalities were significantly faster on the expected side even though the target modality was entirely unpredictable. Chica et al. [101] compared the endogenous orientation of spatial attention to the tactile and visual targets under intramodal and cross-modal spatial cuing conditions. Significantly larger expectancy effects were observed in the intramodal cuing conditions when compared with those in the cross-modal cuing conditions in both haptic and visual stimuli experiments. Therefore, the authors concluded that the endogenous orientation of spatial attention should not be considered to be a purely supramodal phenomenon. This result indicates that attention performance is sensitive to the conditions of either unimodal or multimodal sensory stimuli.

The aforementioned studies on multisensory stimuli demonstrate the potential of integrating the haptic channel with the visual/auditory channels for attention training. However, it is unclear what criteria should be followed for combining different channels to obtain an effective attention-training outcome.

4 Attention training via the efferent pathway

In this section, we summarize previous studies related to the effect of force or motion control tasks on attention modulation. These studies demonstrate the possibility of training attention through the efferent pathway of the haptic channel. In addition, they provide a foundation for studying the ability of haptic control tasks to enhance attentional control and demonstrate diverse possibilities for the development of manipulation-based attention-training tasks.

4.1 Effect of force control on attention

To explore potential methods for training attention using the efferent pathway, haptic devices that can provide vivid force feedback have been used for attention assessment or training in several studies. Using a force feedback device and interactive virtual scenes in a three-dimensional space, Gerber et al. [102] assessed the level of engagement in a computer-based simulation of functional tasks for people with chronic TBI. The authors concluded that the haptic devices are capable of capturing objective data that provide useful information about the fine motor and cognitive performance. Because attention deficits are common in patients after TBI, Larson et al. [103] evaluated the feasibility of applying VR and robotics technology to improve the attention of patients with severe TBI during the early stages of recovery. The participants performed a customized sustained attention remediation task in an interactive virtual environment that integrated both the visual and haptic stimuli. The results indicated that a treatment condition that included haptic cues produced improved performance when compared with that observed in the control condition in which haptic cues were not provided [103]. Both the groups involved hand movements but the control group did not include haptic feedback. Therefore, haptic stimuli appeared to play an important role during the training process. Dvorkin et al. [49] also found that interactive visual-haptic environments can be beneficial for attention training in severe TBI patients during the early stages of recovery. They conducted a comparison between three conditions (no haptic feedback, a break-through force, and a haptic nudge), and the results revealed that only patients under haptic nudge cues benefited from the training.

As previously mentioned, a fundamental question involves identifying the types of haptic interaction tasks that are effective in attracting people's sustained attention or inciting intense concentration from people. Previous studies have illustrated the crucial role of attention in accomplishing accurate force control tasks. Based on the experimental results of isometric force production, Lohse [104] claimed that the focus of attention significantly affected the accuracy based on which the subjects generated force. Chen et al. [105] observed that children with ADHD have a poor ability to maintain stable force control while throwing balls. Motor problems have been frequently described in association with ADD and ADHD, and it has been estimated that 50% of all children with ADHD have a type of motor dysfunction [106]. These studies illustrate the critical role of attention in the production of an accurate force. The observations imply that the force control tasks demand a high level of attention and can be used as a training tool to incite intense concentration from the users.

In a 5-day longitudinal study with one test group and three control groups, Wang et al. [99] found that accurate force control tasks with a pure haptic feedback can enhance short-term sustained attention. As depicted in Figure 3, participants were trained in a force control task during which the external information obtained from the visual and auditory channels was isolated and only haptic feedback was provided. Further, the trainees were instructed to exert a target force within a predefined tolerance for a specified duration (i.e., dwell time). The allowable force tolerance was adaptively modified to elicit the full engagement of the participants. As illustrated in Figure 4, the scores of the three attention tests demonstrated a significant improvement in different aspects of sustained attention for participants in the test group when compared with that for the participants in the control groups. This result demonstrates the efficacy of force control tasks in the promotion of short-term focused attention. However, the neural mechanism underlying the force control tasks is unclear. One method to explore the underlying mechanisms is to perform physiological measurements, such as EEG or fMRI, during the haptic training task.

Dexterous force control tasks combined with the rapidly changing visual cues require considerable attention and can motivate the participants to immerse themselves in various tasks. Yang et al. [66] introduced a visual-haptic game of stimulus-response tasks using fingertip pressure control in an immersive virtual environment (Figure 5). The users were instructed to press a force sensor using either the index or middle finger of either hand. In each trial, users had to maintain a constant force within an expected tolerance range in the required response time. An adaptive strategy was proposed to tune the difficulty level of the task to match the force control performance of the user. This strategy produced an approximately

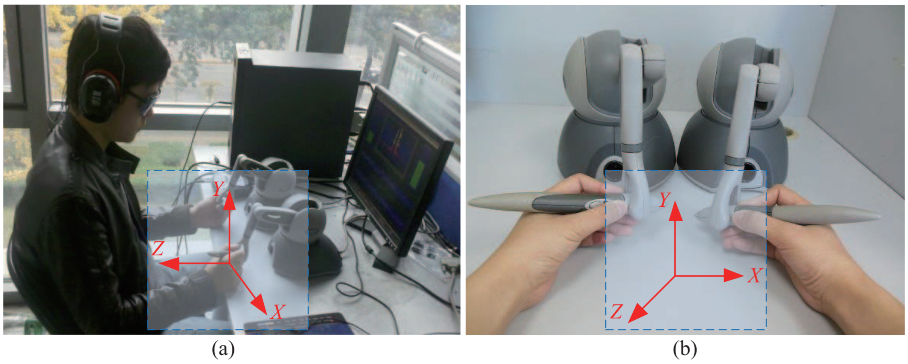


Figure 3 (Color online) The hardware system used for haptic training. (a) Subject held the stylus of two haptic devices and wore eye-shielding glasses and noise-resistant headphones. He used his right hand to grasp the handle of a haptic device to exert a constant force against the virtual wall. The force control status was obtained based on the vibration cues using the haptic stylus in his left hand. (b) Detailed view of bimanual operation using two haptic devices.

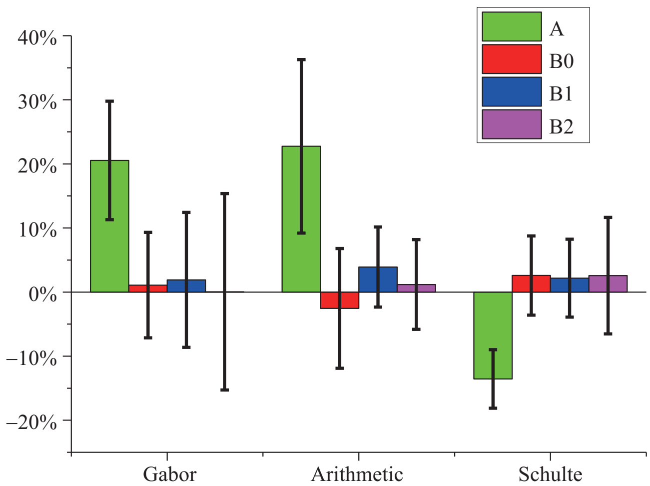


Figure 4 (Color online) Comparison of the performances of the test group and three control groups in attention tests. Error bars represent the standard error of the mean. In the legend, A represents the test group, whereas B0, B1, and B2 represent the three control groups. The ordinate represents the improvement in the post-test scores when compared with the pre-test scores. It should be noted that for the Schulte test, the negative value in case of group A represents the reduced time cost, which implies improved attentional control after haptic training.

constant success rate in maintaining user interest and motivation. For each trial, an immediate reward or punishment feedback was provided via audio and visual signals, which were designed to motivate the participants to engage in the game. The experimental results obtained from six participants indicated that the proposed strategy was able to obtain the expected success rates. However, a longitudinal study is necessary to evaluate the effects of the game on enhancing attention control skill.

Recently, Peng et al. [107] developed an attention-training game that combined multisensory channels, including haptic, visual, and audio channels. In the proposed game, users were required to press a force sensor using either the index or middle finger of both hands. To be successful in a trial, users had to swiftly respond to the visual cues by producing an accurate fingertip force within an allowable duration. The difficulty levels of the task were dynamically adjusted using an adaptive model to achieve a constant success rate. Twelve trainees were subjected to pre- and post-tests during the first and last day of a longitudinal experiment to examine the efficacy of training and its effect on the SART and Stroop tasks. The results of these two typical batteries of attention test demonstrated that significant improvements could be observed after 5 days of attention training.

Figure 5 (Color online) Immersive visuo-haptic game comprising stimulus-response tasks using fingertip pressure control in a virtual reality environment.

4.2 Effect of motion control on attention

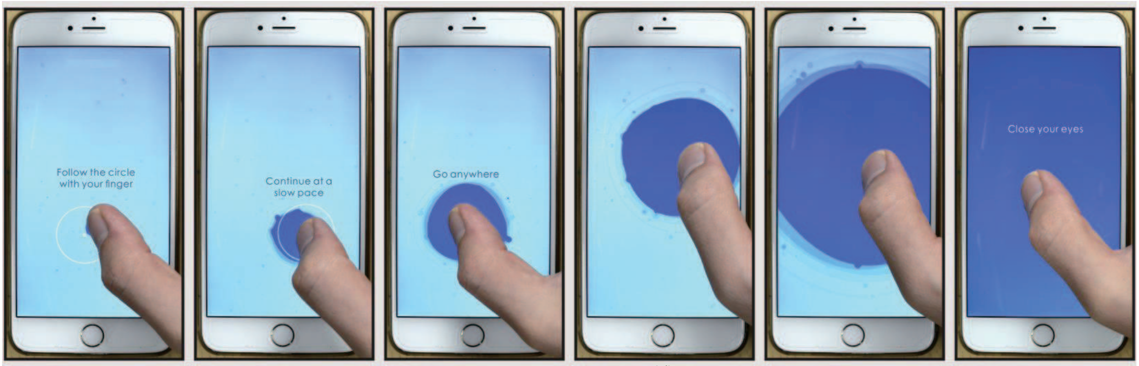
Attention plays an important role in the regulation of the motor system. Lohse et al. [108] found that internal attention (focusing internally on one's body mechanics) reduces the movement variability in individual bodily dimensions (positions and velocities of effectors), whereas external attention (focusing externally on the effects of one's actions) minimizes the movement variability in task outcome. This implies that accurate motion control tasks demand a high level of attention and can be used as training tools to incite intense concentration from the users and enhance their attentional control. In addition, these tasks can be used for motor control training.

Unlike other parts of the human body, tasks involving hands have been extensively studied in the field of haptics [69]. Niksirat et al. [109] presented a framework for interactive mindfulness-based mobile applications that allowed users to regulate their attention according to their abilities and conditions. The framework was motivated by the attention-regulation process and contained two components: relaxation response and attention restoration theory. As demonstrated in Figure 6, the users were required to freely move their fingers over the screen of a mobile phone repetitively, continuously, and slowly. By exploiting the slow and repetitive parameters of the users' actions, the proposed approach assessed whether a user's mind was wandering or whether it was focused on the task. Five days of training were conducted, and the results of ANT indicated that consistent training using the proposed slow motion control tasks significantly affected the executive attention network. However, there were no significant effects on the alerting or orienting networks.

Dexterous and coordinating movement involving hands, arms, fingers, and legs has demonstrated the potential for enhancing the attention and movement skills as well as improving the social behavior problems in children with ADHD [110]. Complex motor training has also demonstrated the effect of improving sustained attention [111]. These results suggest that skilled movements and coordination tasks with hands or fingers as well as bodily exercises can be promising candidates for training attention.

4.3 Effect of bimanual coordination on attention

Bimanual coordination deficits are a problem in ADHD, and children with ADHD exhibit significant variability with respect to both the velocity and coordination during bimanual movement tasks [112]. Motor coordination and attentional load have a common origin, and bimanual coordination dynamics stability is linked with the attention [113]. Bimanual movement accuracy has been demonstrated to benefit from focusing attention [114, 115]. This implies that accurate bimanual coordination movements are attention-demanding, which is a promising methodology for designing the attention-training tasks.



(a) (b) (c) (d) (e) (f)

Figure 6 (Color online) Attention training using a slow and repetitive motion. (a) First, a user selects a preferred color for meditation (here, the color is blue). Next, the user begins to follow the white circle with the finger on the screen while the audio is playing. (b) An amorphous floating air bubble appears. The screen text instructs the user to move the finger slowly. (c) The user freely moves the finger over the entire screen repetitively, continuously, and slowly. (d) Pause continues to generate feedback while there is a slow, continuous, and repetitive finger movement. The floating bubble of air gets larger, and audio continues to play. (e) The bubble size increases, provided that the user does not stop moving the finger and does not move it too quickly. If the movement is not sustained within these parameters, the bubble fades away to remind the user to return to the activity and maintain necessary attention. In case of lost attention, the user must repeat the process from step (b) to return to a properly attended interaction. (f) Finally, the floating air bubble covers the entire screen, and Pause instructs the user to close his/her eyes and continue the finger movement. Users should continue moving in a slow and repetitive manner; otherwise, the feedback fades to remind the users to return their attention to the task. (Adapted from Niksirat et al. [109], @Copyright 2017 Association for Computing Machinery, Inc.)

Complex bimanual motor learning causes specific changes in activation across different regions of the brain. However, additional studies are required to explore the manner in which motor learning changes the functional connectivity between these regions and whether it is influenced by different feedback modalities. Bimanual manipulation is closely associated with the corpus callosum [116,117], which is the largest white matter structure in the human brain, connecting the cortical regions of both the hemispheres. Therefore, further understanding the mechanism of the corpus callosum is necessary for exploring potential methods to train attention using bimanual manipulation tasks.

4.4 The potential of attention training via efferent pathway

Novel attention-training approaches can be explored by designing dexterous motion and/or force control tasks that heavily rely on the haptic channel. For example, a starting point can involve designing different types of precise pressure control tasks and comparing the attention-modulating effect under varied experimental conditions, such as different muscles activated in the task, different levels of task difficulty, and different sensory channels, for producing a feedback signal to rectify the motion/force control errors.

In addition to the existing force/motion control tasks that display certain training effects, rigorous longitudinal studies with a long duration (e.g., several weeks) should be performed. These studies can assist in validating the effect of haptic manipulation tasks on enhancing attention control skill. Furthermore, it is necessary to explore and compare the attentional modulation effects when trainees perform different types of motion or force control tasks. The biological markers for assessing the attention levels of trainees can be explored using the neurophysiology and neuroimaging tools, including EEG, fMRI, and functional near-infrared spectroscopy (fNIRS). These results can provide quantified evidence for understanding the underlying neural mechanisms for modulating and enhancing attentional control via haptic manipulation tasks.

In comparison with the previous training tasks using visual or auditory channel, the dominant role of the haptic channel can be enhanced by increasing the required accuracy of the force/motion control task, imposing a considerable challenge on the motor control abilities of individuals. It remains an open question whether the increased manipulation accuracy benefits attention training.

For haptic control tasks involving bimanual coordination, one topic can be explored involves the coordinating mechanisms of the left and right hemispheres of the brain, which can help to understand the regulation mechanism of the corpus callosum in attention training. Because the left and right hands of humans are contralaterally controlled by the right and left hemisphere of the brain, respectively, we can compare the effects of two types of tasks on attention regulation (i.e., the left and right hemisphere working independently or synergistically). To compare the various haptics-related attentional studies mentioned above, the major features of the representative studies are summarized in Table 1 [49,64,66,77,78,99,103,109,118].

5 Future directions

Based on the correlation demonstrated in previous studies between the attention and haptic channel, several future research topics that aimed to explore effective haptics-mediated attention-training approaches are introduced and elaborated in this section.

5.1 Effective training approaches based on the Hebbian learning theory

Visual tasks, such as action video games, can lead to the improvement of attentional control such as visual attention and executive control [9, 31, 35]. Anguera et al. [9] demonstrated that a custom-designed video game can enhance the cognitive control abilities, including sustained attention and working memory, of elderly people. Their experimental results support the role of interference during gameplay as a key mechanistic feature of the training approach. When the participants were motivated to simultaneously engage in two tasks, they developed their cognitive control skills by learning to resolve interference and accomplish multiple objectives. This result indicates that being immersed in a challenging, adaptive, and high-interference environment for a prolonged period of time leads to enhanced cognitive performance in untrained tasks.

Due to the similarity of the neural signal transduction among visual, audio, and haptic channels, it is reasonable to infer that haptic interaction tasks can reproduce the aforementioned mechanism created by video games. The feasibility can be explored using the following two-step approach that can lead to the neuroplasticity of the attentional brain network.

In the first step, challenging and adaptive haptic tasks can be designed that produce an intensive attention workload and high interference. By completely exploiting the perception and manipulation abilities of the human haptic channel, we can design various tasks that ensure that users are immersed in the tasks, maintain an alert state, and solve conflicts between multiple haptic tasks. These haptic tasks can produce a similar or stronger interference effect when compared with that obtained using visual tasks. Furthermore, we can design multisensory tasks that simultaneously use haptic, visual, and auditory channels. This approach can produce a better outcome in attention training than training tasks using an individual channel.

In the second step, we can conduct multiple several-week-long training sessions, which can lead to the reinforcement of attentional control through iterative activation of the attentional network, including the alerting, orienting, and executive control networks [1, 6, 8, 94]. According to the principle of Hebbian learning [119], repeated and simultaneous activation of two neurons can facilitate the formation of strong associations between them. In custom-designed haptic perception and/or manipulation tasks, the design goal is to simultaneously activate the attentional network and the haptics-related brain network (somatosensory cortex and/or motor cortex). After multiple training sessions lasting several days or weeks, plastic changes may occur in the attentional network. More importantly, the enhanced attentional control may potentially be transferred to other cognitive tasks that do not involve a haptic channel [99]. Attention training through external sensory stimuli based on the Hebbian learning theory is illustrated in Figure 7.

Previous studies on modulating and/or training attention using the afferent and efferent pathways of the haptic channel denote the need for systematic exploration of the possible methods to exploit the human haptic channel for training attention. It is important to identify tasks that can achieve the effect

Table 1 Summary of the attention-training studies involving the haptic channel

Authors & years	Training method	Sensory channel	Aim of attention training or modulation	Subjects	Groups	Procedure	Duration	Validation methods	Results
Young et al. (2003) [64]	NA(a)	Visual, haptic	Visual spatial attention	10 (5 F(b), 22 yr(c))	2 groups (80% validity, 20% validity)	Conduct the visual stimuli orientation change-detection task with 20% or 80% validity haptic cues feedback	3 sessions $\times$ 22 runs $\times$ 60 trials	Visual stimuli, flicker paradigm	• Detection time was significantly decreased with the valid haptic cues. • It is natural and intuitive to use haptic cues to reorient a person's visuospatial attention.
Draganski et al. (2004) [118]	Juggling	Visual, haptic	To visualize learning-induced plasticity in brain	24 (21 F; mean 22 yr, sd(d) 1.6 yr)	2 groups (jugglers and non-jugglers)	3 steps of brain scan: • 1st: before learning as the baseline; • 2nd: skilled performance; • 3rd: 3 months later.	3 months	Whole brain magnetic-resonance imaging	• Juggler showed a significant transient bilateral expansion in gray matter in the mid-temporal area (hMT/V5) and the left posterior intraparietal sulcus. • Perception and spatial anticipation of moving objects is a stronger stimulus for structural plasticity in the visual areas than in the motor areas.
Larson et al. (2011) [103]	VR and haptic feedback	Visual, haptic	Sustained attention	15 TBI patients (2 F)	One group with three conditions (nudge, balloon, no force)	Patients with TBI were trained by task in VR with visual and/or haptic feedback in two days.	2 days	Performance on time to stay on task	• Treatment with haptic cues led to better performance than treatment without haptic cues. • Haptic feedback with the nudge force was more effective than haptic feedback with the repulsor force.
Dvorkin et al. (2013) [49]	VR and haptic feedback	Visual, haptic	Sustained attention	21 inpatients with severe TBI (4 F)	One group with three conditions (nudge, break-through, no force)	Patients with severe TBI were trained by task in VR with visual and/or haptic feedback in two days.	2 days	Performance on time spent and number of targets required	• There was an overall beneficial effect of the haptic nudge when compared with the no force condition and the break-through condition.
Wang et al. (2013) [77]	SSSEP(e)	Haptic	Effects of specific frequency vibrotactile stimulation on the EEG signal	22 (4 F)	2 groups (SMR group, Alpha group)	Pre-EEG, training, post-EEG	15 min	EEG (SMR and Alpha)	• 15 Hz sinusoidal vibrotactile stimulation increased the SMR level. • 10 Hz sinusoidal vibrotactile stimulation decreased the alpha level.
Wang et al. (2014) [99]	Adaptive force control	Haptic	Short-term focused attention	40 (17 F, 20–27 yr)	1 test group and 3 control groups (A, B0, B1 and B2)	Pre-test, training, post-test	5 days	Three attention tests: Gabor patch, Schulte square, arithmetic.	• Adaptive force control tasks with pure haptic-feedback-enhanced focused attention over a short time frame. • The ability to enter the focused attention zone can be transferred to other non-haptic attentional tasks.
Zhang et al. (2016) [78]	Sustained tactile stimuli (SSSEP)	Haptic	Short-term attention	20	2 groups (test group, control group)	Pre-EEG, training, post-EEG	16 min	EEG (SMR), TOVA	• It is feasible to enhance short-term attention with haptic-based brainwave entrainment.
Yang et al. (2016) [66]	Adaptive visual-haptic game	Visual, haptic	Sustained attention	6 (4 F; mean 23 yr)	1 group	Visual-haptic game with adaptive strategy	NA	NA	• Developed a visual-haptic attention-training game based on an effective adaptive strategy.
Niksirat et al. (2017) [109]	Slow, continuous finger movement	Visual, audio, haptic	Sustained attention	18 (8 F, 20–34 yr; mean 27 yr, sd 4.3 yr)	2 groups (training group, control group)	Slow and continuous finger movement, attention-regulation process	5 days	ANT, heart rate, EEG	• Five days of training using the mindfulness-based mobile applications improved the response times of the alerting network.

(a) NA = not applicable; (b) F = female; (c) yr = year; (d) sd = standard deviation; (e) SSSEP = steady-state somatosensory evoked potential.

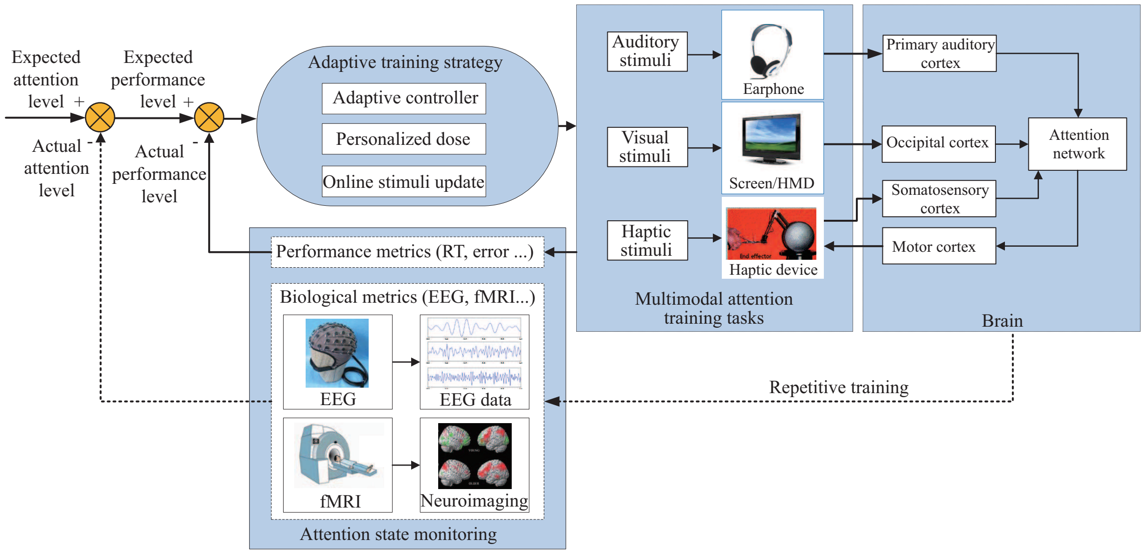


Figure 7 (Color online) Closed-loop attention training through multiple sensory stimuli based on the Hebbian learning theory.

of neural plasticity (i.e., whether the trainees' attentional control can be significantly improved after a long period of training by haptic training tasks). In longitudinal attention training studies, the challenge is to motivate the trainees to engage in a training task after multiple training sessions. An important research topic is the exploration of parameter optimization and adaptive strategies for the haptic training tasks [34].

Previous studies on perceptual training [120, 121] illustrated two fundamental design elements that drive neuroplasticity. One is that continuous performance feedback at multiple levels of the training game provides repeated cycles of reward to the user. The other is that training is adaptive to the trainees' game performance in the moment; adaptivity is achieved using psychophysical staircase functions that increase the task difficulty in response to good performance and reduce the task difficulty in response to poor performance. The staircase function is often used to keep a task challenging at a success rate of 75%–85% at which the user is optimally engaged. Thus, continuous performance feedback rewards and adaptive task difficulty serve to personalize the training with respect to the cognitive capacity of each individual, improving the attentional control abilities over time. In haptic training tasks, the adaptive strategies for changing the training task parameters within or across the training sessions have not yet been studied.

For example, for passive haptic perception tasks without any body movement, systematic studies should be conducted to observe the effects of varying stimuli parameters on attention training. The potential parameters include different sites on the skin for haptic stimuli (e.g., fingertip, wrist, and neck), different haptic stimuli (e.g., normal or tangential force and vibration), and different stimulus parameters (e.g., frequency and amplitude). The difficulty level of the haptic perception tasks can be increased as follows. The inter-stimulus interval between adjacent stimuli can be decreased, the presenting duration of the target stimuli can be random, and the magnitude of the stimuli can be adjusted to approach the just noticeable difference of humans [122]. These changes can significantly challenge the detection and discrimination abilities of humans.

The concept of closed-loop automatic control can be introduced into the haptics-mediated attention-training paradigm, as illustrated in Figure 7. While various haptic interaction tasks can be used to enhance the attentional control, an adaptive controller can be designed to dynamically tune the task parameters, which serves to maintain a high level of engagement by matching the difficulty level of the training task with the abilities of the trainee during the training process.

There are two loops for adaptively tuning the training strategies and/or parameters to produce an attention-training effect. In the inner behavior digital closed loop, performance metrics, such as the response time and force control error, can be used to measure the performance and engagement levels of the trainees during the training task. This loop links the behavioral performance metrics with the adaptive modulation of the training task.

In the outer neurodigital closed loop, biological markers, such as EEG signals in specific frequency bands or fMRI network connections in specific brain regions, can provide feedback about the attention levels of the users. This loop links the neuronal performance and physiological measures with adaptive mechanics. As proposed in cognitive enhancement studies [9, 37], the usage of neuronal performance as a feedback signal for task adaptivity can generate more rapid, efficient, and specific circuit plasticity than that obtained using the behavior performance alone as a feedback signal. The neurodigital closed loop offers an ability to selectively train and refine overwhelmed neural processes that govern the final attentional behavioral outcome.

In addition, promoting and retaining the interest and enthusiasm of participants throughout the task is an important factor that affects the training outcome. The learning process is multifactorial and requires the trainee to be in a specific state for ensuring the effectiveness of the training task and to enable learning. In addition to the training task itself, the learning/training outcomes can also be affected by the instructions and feedback provided to the trainee and the environment in which training is conducted. For example, motivation is an important factor in the reinforcement of learning and for obtaining effective outcomes of instruction [123]. The ARCS (attention, relevance, confidence, and satisfaction) model defines four major conditions that must be satisfied for the individuals to become and remain motivated. Another lesson can be learned from the flow theory, which motivates trainees by maintaining a balance between their skills and the demands of the task to obtain a flow state [124].

5.2 Validation of the neuroplasticity effect

A gold standard for attention assessment must be developed to validate the efficacy of the haptics-mediated training approaches. It is necessary to explore the type of behavioral tests or human physiological indicators that can be used to measure the attention level of trainees and to measure the degree of attentional control. By comparing the performances and indicators before and after haptic training, we can determine whether the attentional control has been improved.

Two types of validation approaches can be used to provide evidence about attention enhancement for the haptics-mediated training approaches, including the attention test tasks to provide behavioral evidence, such as the ANT developed by Fan et al. [6], and neurophysiological and/or neuroimaging signals to provide biological evidence [12, 125, 126]. Using these two approaches, the neuroplasticity effect of the haptics-mediated training can be validated by observing the improvement in behavior performance between a post-training test and a pre-training test. In addition, the effect can be validated by observing the changes in the activated brain areas observed based on a post-training test and a pre-training test.

Behavioral evidence can be obtained by designing a series of test tasks for measuring the attentional control skills before and after haptic training. Typical attentional control tasks [127] include the ANT [6], TOVA [128], continuous performance test [129], SART [130], attentional blink, task switching, trail making, Stroop task, and card identification task [131].

Physiological evidence can be obtained by comparing the brain's physiological signals before and after training. These can be regarded as evidence for the enhancement of the attentional control abilities. It is necessary to explore the type of physiological signals that can effectively characterize a user's level of attentional control. For example, EEG and fMRI can be used to measure the strength of neural activities in different brain regions and the changes in connection strength between any two different brain regions [132]. Clayton et al. [133] proposed an oscillatory model of sustained attention that included frontomedial theta oscillations, inter-areal communication via low-frequency phase synchronization, and selective excitation and inhibition of cognitive processing through gamma and alpha oscillations. This model can be potentially used to guide the development of the attention-monitoring EEG systems and identify attentional lapses during the attention-training process [133].

5.3 Neural mechanism of the haptics-mediated attention training

To identify effective methodologies for enhancing attentional control, it is necessary to possess an understanding of the neural activities of the brain during focused attention and, more importantly, to identify the neural mechanisms that can lead to the plasticity of attentional control.

Using neurophysiological and neuroimaging methods for monitoring the changes in brain activity before, during, and after haptic training, the physiological and neural attention mechanisms can be revealed by analyzing the brain regions activated during the training process, the connection strength between brain regions, and the typical changes in the brain tissue area and volume. Typical methods, such as brain traceability analysis, nonlinear dynamic analysis, brain connection network analysis, and time-frequency analysis, can be used to reveal the underlying mechanisms [134, 135].

Characterizing the training-induced changes with respect to functional connectivity in case of the brain networks involved in attention training is a promising topic. Network science, which is largely based on graph theory, has been extensively used for investigating the brain network architectures [134, 135]. The topological properties of a complex network can be quantified by a wide variety of measurements such as small-worldness, modularity, hierarchy, centrality, and network hub distribution [134]. Many studies have been conducted to identify the underlying areas of the brain during sustained attention. Hopfinger suggested that the networks of cortical areas, including the superior frontal, inferior parietal, and superior temporal brain regions, are involved in top-down attentional control. Buschman et al. [136] used electrodes to simultaneously record the activities in three cortical regions. Bottom-up shifts of attention were initially observed in the parietal cortex, whereas top-down shifts of attention were initially observed in the frontal cortex [136].

Posner and Petersen [3, 94] proposed that attention involves a network of anatomical areas and that these anatomical areas play different roles. They also proposed a classical attentional network, comprising three components, i.e., alerting, orienting, and executive. Each component has a discrete anatomical basis and represents a different set of attentional processes.

In addition to the ANT network proposed by Fan et al. [6], other attention networks have been introduced. In a review by Langner and Eickhoff [5], evidence was provided for a primarily right-lateralized cortico-subcortical network responsible for vigilant attention maintenance. The putative core network involves the dorsomedial, mid- and ventrolateral PFC, anterior insula, parietal areas, and cerebellar vermis, thalamus, basal ganglia, and midbrain [5].

Based on the neuroimaging of the brain attention networks, many studies have been conducted to explore the possible underlying neural mechanisms of attention training using video games or meditation. These studies provide a foundation for exploring the neural mechanisms of haptics-mediated attention training.

Several studies have explored the neural mechanism of video games in training attention. Green et al. [137] explored the neural mechanisms of attention training through action video games and reported that the games improved the trainees' abilities with respect to probabilistic inference in unknown environments. After completing training using these games, the trainees possessed the self-learning ability in a new task environment [137]. Anguera et al. [9] demonstrated that the video games improved sustained attention in elderly people using theta (4–7 Hz) EEG power from the midline frontal of the medial PFC and long-range theta coherence between the frontal and posterior brain regions as the physiological markers of sustained attention. Byers and Serences [138] found that training may play a role in optimizing the effectiveness of top-down attentional control by improving the efficiency of the sensory gain modulations, regulating intrinsic noise, and altering the read-out of sensory information.

Many studies have also examined the neural mechanisms of meditation exercises in training attention. Lutz et al. [139] observed that meditation training improves the functional connectivity between the anterior cingulate and the striatum. Tang and Posner [8] proposed that attention training involves changes in the anterior cingulate and lateral prefrontal areas; this is hypothesized to primarily occur through increased connectivity between the two areas. Wells et al. [140] determined that for subjects with MCI, the functional connection between any two of the posterior cingulate cortex, bilateral medial PFC, and left hippocampus becomes stronger than that in the control group after meditation was practiced.

Additional studies are required to uncover the neural and physiological mechanisms of neural plasticity, to identify the brain areas and/or functional connection networks that produced plastic changes, and to explore why these changes occurred after haptics-mediated attention training. Based on the results obtained from brain network analysis, the differences between various haptic training tasks can also be studied to reveal different neural mechanisms. For example, it would be interesting to compare the different mechanisms of haptic perception and motor control tasks in attention workload modulation and explore the type of adaptive parameter tuning strategies that can achieve satisfactory attention-training outcomes.

Finally, considerably diverse neuroimaging methods can be explored to reveal the neural mechanism of haptics-mediated attention training. The existing studies mainly focus on the task-induced brain activity measured by EEG or fMRI, ignoring the neuroimaging data of other modalities, such as resting-state fMRI, DTI, and anatomic imaging (e.g., T1 weighted MRI). With respect to the task-induced brain activity, the neuroimaging data from these modalities may reflect the intrinsic brain changes induced by haptic training and may, therefore, reveal the neural markers related to attention. In addition, to overcome the constraint of maintaining a static body posture during fMRI measurement, novel imaging methods, such as fNIRS, can be used to observe the neural activities during haptic interaction tasks that involve frequent movements of a user's hands or arms.

5.4 Transfer effect of haptics-mediated attention training

Further exploration is required to evaluate whether the attentional control abilities acquired through haptic training can be transferred to other cognitive tasks not related to the haptic channel. This can serve to determine the scope and potential application value of haptics-mediated attention training.

The cognitive training literature provides controversial results with respect to the transfer effect. Some studies [141] have demonstrated that the performance improvements after training were usually task-specific rather than general or transferred improvements. Oei and Patterson [142] concluded that cognition improvements caused by video game training should be considered to be near-transfer effects. However, other studies have demonstrated the possibility of far-transfer after training [143] although the ability of training to be generalized remains controversial [144]. Anguera et al. [9] demonstrated that performance improvement caused by video game training can transfer to untrained cognitive control abilities such as sustained attention and working memory. This result indicates that the training effect is not always modality-specific and that it can be transferred to other modalities. Jaeggi et al. [145] presented evidence for the transfer of the practice effect from training in a working memory task to fluid intelligence. The underlying mechanism associated with this transfer may be explained as follows. If a brain's sub-network engaged in a trained task overlaps with other networks related with untrained tasks, the other networks may be strengthened to some extent. Consequently, this would serve to improve the cognitive performance in the untrained tasks.

Tang and Posner [8] classified the existing attention-training approaches into two strategies: network training and state training. Network training refers to the use of a cognitive task to exercise specific brain networks related to attention, whereas state training refers to the use of designed tasks to develop a brain state that can influence attention and other networks. The authors argued that the degree of transfer of obtained skills to untrained tasks remains unknown for network training. They proposed that state training can produce a transfer effect; however, there remain open questions, including the identification of the underlying mechanisms and determination of the duration of the improved attention abilities.

As illustrated by a study involving students with ADHD, enhancing attentional control can improve the students' learning outcomes [40,146]. However, it is unknown whether this benefit is applicable in the case of students without mental disorders. Therefore, rigorous user studies must be performed to validate the impact of novel haptics-mediated attention-training approaches on students with various physical and mental conditions.

Therefore, the tasks for validating the transfer effect of haptics-mediated attention training should have a relatively large coverage to explore the extent of transfer of the acquired attentional control skills. The validation tasks can include tasks using other sensory channels as well as real-world attention-demanding tasks. For example, the validation tasks that considerably differ from haptic training tasks should be tested, such as visual perception tasks, mathematical calculations, and reading comprehension.

5.5 Challenges associated with haptic technologies

Previous studies have indicated that force control task using desktop haptic devices can promote focused attention [49]. Recently, flexible and wearable haptic devices have been developed with an integrated force and tactile display [69,147]. These devices can be used for developing novel attention training tasks. In addition to the fingertips, hands, and upper limbs, haptic cues can also be designed to target lower limbs, including the legs and feet. For example, various force feedback devices have been developed for the lower limbs [148–151]. These devices produce varied force cues on users' feet and can be used to design perception-based attention-training tasks. Furthermore, these devices can record the motion or output force of the users' lower limbs during locomotion tasks. Whole-body manipulation-based attention-training tasks that require synchronized motion control between upper and lower limbs can be designed. Thus, dexterous whole-body movement tasks can be an important training approach for recruiting and training users' attentional control skills.

With the advancement of the haptic rendering technology, there is potential for developing various bimanual dexterous manipulation tasks with adaptively changing difficulty levels. This may include six-degrees-of-freedom haptic rendering algorithms for simulating multiregion contacts and deformable objects [152, 153] such as delicate grasping and object manipulation between a virtual hand and a deformable object. Immersive VR games with intensive haptic perception and motor control tasks are expected to significantly draw the attention of the players [103]. Based on versatile interaction scenarios, the effects of different haptic training tasks on attention enhancement can be compared.

To observe the neuronal activity during haptic interaction tasks, new haptic devices that are compatible with fMRI should be developed. Combining haptics and fMRI can allow us to non-invasively study the manner in which the human brain coordinates movement during complex manipulation tasks; however, avoiding associated fMRI artifacts remains a challenge. Various approaches have been proposed to attempt the elimination of motor artifacts in fMRI measurements. These approaches include avoiding electromagnetic actuation for haptic interfaces [154,155], placing actuators outside the scanner room [156], and using simple devices [157]. Such approaches usually lead haptic interfaces to be suitable only for a limited set of motor tasks. Recently, Menon et al. [158, 159] developed an fMRI-compatible haptic device for real-time interaction across the scanner workspace. The remaining challenges are to develop a transparent six-degrees-of-freedom fMRI-compatible haptic interface that can support a multi-kilohertz control rate and to demonstrate the fidelity of the haptic display at high magnetic field strengths during high-resolution multiplexed scanning with sub-millimeter and millisecond timescales [159].

6 Conclusion

Attentional control can be enhanced through training. However, no systematic studies have investigated a methodology to fully exploit the human haptic channel during training. Because of the fundamental mechanism of attention and the unique features of the haptic channel, attention training mediated by haptics offers considerable potential.

Haptics-mediated attention training is a cross-disciplinary study that involves haptics, cognitive neuroscience, and psychophysiology. The exploration of the psychological and neural mechanisms of attention in tasks using the haptic channel may also promote the understanding of the neuroplasticity mechanism in humans.

This study proposes a novel application of the haptic technologies, which enhances the human brain's capacity for maintaining sustained attention using the haptic channel. Because the haptic interactions, such as the force control ability, is a natural human instinct, the existing computer games can be potentially redesigned by incorporating accurate force control scenarios, increasing the players' attentional workload. Further, these games can be used by various populations, including elderly individuals and those with mental disorders such as ADHD. These games can also benefit certain specialized attention-demanding professionals such as airport security screeners and pilots.

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