Direct versus Indirect Visual Feedback: the Effect of Technology in Neurorehabilitation

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***Abstract*— Visuomotor feedback and its impact on performing and learning movements is an extensively studied field, both through the use of experiments under different types of visuomotor feedback, as well as through neurophysiological studies. Neurorehabilitation of the upper-limb relies heavily on repetitive targeted movements and in recent decades, the introduction of instrumented and robotic devices coupled with computer screens have substituted the existing direct visual feedback of traditional practice with an indirect feedback. However, the impact of such a shift has not been studied.**

Putting in perspective the literature on these different aspects, this paper shows that there seems to be little indication that the feedback type may significantly affect the neurorehabilitation outcomes. Nevertheless, despite the intrinsic difficulties in directly observing the effects of the introduction of indirect visual feedback in neurorehabilitation practices, it is of interest to investigate further this specific aspect of the newly introduced technologies.

I. Introduction

When one makes a goal-directed movement, such as reaching for a coffee mug on a desk, a range of senses are used to ensure successful goal completion. The use of sight as feedback in such movements is termed visuomotor feedback. Different types of visuomotor feedback can be considered. In most everyday tasks, humans use direct visuomotor feedback — that is, they are capable of viewing their limb and the environment directly, such that, for example, they can see both the mug and their hand, and use this to modulate their movements. However, indirect feedback is also possible — when, for example, one uses a computer mouse to drive the pointer on a screen. The goal of the movement is presented on the screen and the position of the user's hand drives the cursor on the screen.

Due to its importance in human motor control, the effects of modifying the visuomotor feedback loop has been studied in many ways, through the use of mirrors, lenses and computer screens. It has been found that such modifications can significantly affect the performance of movements, but also that the human mind can adapt to or learn these changes, to ensure successful completion of the task.

Rehabilitation after neurological injury, or neurorehabilitation, is one area which heavily leverages goal orientated movements. Neurorehabilitation aims to take advantage of brain plasticity and cortical recovery and reorganisation to recover motor function. Due to the extremely variable nature of impairments resulting from neurological injury, neurorehabilitation practice is varied in theory and application. However, current practice is driven by the principle of intensive practice of goal-orientated movements [1].

Technology has emerged as a great potential tool in the provision of neurorehabilitaiton, due to its capability to provide engaging exercises, its ability to provide data and even physical support (for example, through the use of robotics) to allow patients to perform additional exercises by reducing therapist dependency. Such technology — often termed "virtual rehabilitation" generally involves the use of computer screens to provide a meaningful goal for the patients' movements, and feedback on their performance. However, this has also led to a change in the mode of visuomotor feedback during rehabilitative exercises. Exercises traditionally have been performed in the 'real-world' with the availability of a direct visuomotor feedback. However, the vast majority of virtual rehabilitation devices instead offer indirect feedback. With some exceptions, the adoption of this technology is thus resulting in a fundamental change in the visuomotor feedback provided during rehabilitation exercises.

Despite this significant change, the effects of such a change to the efficiency and efficacy of rehabilitation have not been investigated. Such an investigation is challenging to perform, due to the vast variability in the presentation of motor impairments and the rehabilitation regimes performed. Therefore, the purpose of the present work is to provide a review of the literature on visuomotor feedback within the neurorehabilitation context and to put it in perspective of the changes introduced by virtual rehabilitation tools. This is achieved in three parts. First, the outcome of experimental studies detailing how different modes of visuomotor feedback affects motor movement and learning are summarised. Secondly, this work discusses the neurological models of visuomotor system and neurological spatial representations. Finally, additional comments are made comparing traditional therapy with virtual rehabilitation, and suggestions regarding its effectiveness are presented.

II. Direct versus Indirect Visuomotor Feedback in Motor Control, Learning and Adaptation

Numerous experiments have been conducted with differing types of visuomotor feedback, and results can be presented on two fronts: how the movements change under the different types of feedback; and how learning/adaptation transfers between different types of feedback.

Experiments in this field are commonly performed on 'reaching' tasks. Movements under different conditions are

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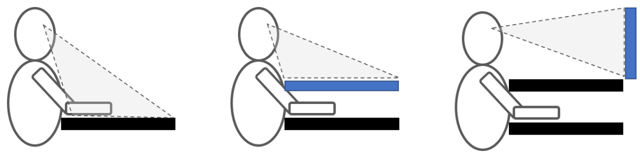

Fig. 1: Types of visuomotor feedback (left to right): Direct: the subject can view their hand directly; Aligned (Indirect): the subject can see a representation of their hand, visually aligned with their physical hand; Unaligned (Indirect) - the subject is presented with a representation of their hand, not visually aligned with their physical hand.

then quantified and compared using metrics such as the accuracy of the movement, the speed of the movement, and the curvature of the movement path.

A. *Defining Types of Visuomotor Feedback*

Conditions within experiments using varying types of visuomotor feedback can be divided into three main categories, summarised on Figure 1. Direct feedback is available when the subject can directly view their hand and the target location. This condition is most similar to everyday tasks. Aligned feedback is provided when the subject cannot see their hand, but is given a representation of the hand which is visually aligned to the location of their hand. Whilst this condition is still indirect, it does not require the subject to transform the relative positions of the target and the hand to a different direction of movement. Finally, in unaligned feedback, the visual representation of the target and the hand is not visually aligned with the actual hand and target. For example, when using a computer mouse, a forward movement at the hand corresponds to a vertical movement on the screen. This last condition also represents the common arrangement encountered in virtual rehabilitation.

B. *Impact on Immediate Performance*

Experimental results in this area show differences in motor behaviour with differing types of visuomotor feedback.

Bo et al. [2] provided a clear comparison of direct, aligned and unaligned feedback in their study. The study involved comparing the movements made when to targets on a horizontal plane under these three conditions, with multiple age groups (4, 6 and 8 year olds, and adults). Their results demonstrated a significant difference in the speed, straightness and smoothness of movements made with direct feedback, and those within the aligned and unaligned conditions — but movements in the latter two conditions did not differ significantly from each other. This is interesting, as it indicates that simply removing direct vision of the hand, and replacing with a virtual equivalent, changes the performance of the task.

Messier and Kalaska [3] conducted a study which also highlighted the difference between movements made with direct and unaligned feedback. The study investigated reaching tasks under 4 conditions (termed 'tasks' in the paper) — of which tasks 1, 2 and 4 have particular relevance for the present work. Task 1 provided direct visuomotor feedback, but the subjects were asked to close their eyes when making the movement, and were not given information about the success or failure of their movement. Task 2 provided unaligned feedback, through the use of a screen with an animation on a vertical plane in front of the subject, and provided this feedback only at the end of the movement (*i.e.* did not allow for movement correction). Task 4 provided equivalent feedback to task 2, but with direct visuomotor feedback. It was observed that the characteristics of the movements in task 2 varied significantly from those seen in tasks 1 and 4, and that absolute error in task 2 was significantly higher than those observed in the other tasks, indicating the difficulty associated with performing this task with unaligned feedback. Messier and Kalaksa suggest that this can be explained by the "additional cognitive operations that are presumably required to translate visual information about target location on the monitor screen into an estimate of the metrics of the desired arm movement". These results are of interest, as it indicates that the switch between direct and unaligned feedback also impacts on the planning of the motor task.

C. *Effect on Learning And Adaptation*

Another key issue with respect to the lens of rehabilitation is the question whether learning or adaptation in one environment transfers to another. With respect to neurorehabilitation, it is essential to ensure that recovery of learning using indirect methods transfers to movements with direct feedback, due to their prevelance in activities of daily living.

Norris et al. [4] provided some evidence indicating that such knowledge can be transferred. Their study compared direct feedback with two types of unaligned feedback — one in which the representation was a live video of their hand (*Video*), and the other in which an animated representation was used (*Cursor*). The motor adaptation was tested through the donning and doffing of wedge prisms which rotated the subjects' visual field by approximately 23°. The results demonstrated differences in the magnitudes of the effects of both donning and doffing the prisms, specifically that the prisms had a larger effect when the subject had direct feedback. The study also investigated the after effect (that is, after the prisms have been doffed) in conjunction with a change in feedback. It is noted that this effect was smaller when one moved from either the *Cursor* or *Video* to the Direct feedback, when compared with moving from Direct to either the Direct, *Cursor* or *Video* feedback. However, the study did not investigate the case of moving from the *Cursor* with Prisms to the Direct with Prisms, which would be most representative of the use of gaming technology in neurorehabilitation.

Lhuisset and Proteau [5] also studied how learning can transfer from one type of visuomotor feedback to another, in a study designed similar to that of Bo et al [2]. This study compared aligned feedback with unaligned feedback across different age groups, through a protocol which required a pre-test of the task with aligned feedback, an 'intervention' of task practice with unaligned feedback, and then a post-test of the task with aligned feedback. Their practice indicated that practice of a task in the unaligned condition does transfer to performance of the task in the aligned condition — particularly with respect to the magnitude of the movement.

These results suggest that a transfer of adaptation or learning can occur between different types of visuomotor feedback, however, do not significantly contribute to a conclusion regarding preference in neurorehabilitation.

III. Neurophysiological Considerations

A second approach to the understanding the roles of indirect and direct feedback in neurorehabilitation is a neurophysiological analysis. This analysis considers how information is processed within the brain during a goal-directed movement task, thus providing an understanding of the differences in brain response when using direct and indirect feedback. This section first discusses the visuomotor brain pathways and brain areas of interest for goal-orientated movements. Secondly, a discussion on how the goal and arm are represented in the brain is presented, relating to the differences between direct and indirect feedback.

A. The Visuomotor Pathways

It has been long established that beyond the primary visual cortex, information follows primarily two cortical streams [6], the Dorsal Stream (DS), connected to the Posterior Parietal Cortex (PPC) and the Ventral Stream (VS) connected to the InferoTemporal Cortex (ITC). In 1992, Goodale and Milner proposed an interpretation of this two-stream model based on 'function'. This interpretation suggests that the Dorsal Stream processes the *information related to actions* and the Ventral Stream is dedicated to *perception and cognitive representation* [7], [8].

Observations of behaviours of neurological patients with damage confined to one area or the other provide evidence for this interpretation. Subjects with lesions in the PPC exhibit optic ataxia, characterised by difficulties in reaching objects and in orienting their hand with an appropriate finger postures for grasping objects. However, patients with optic ataxia have no specific difficulties describing objects including their orientation [9]. Conversely, patients with visual agonosia, due to a lesion in the occipitotemporal region — corresponding to the Ventral Stream —, have difficulties in identifying objects' characteristics (shape, size or orientation) but no difficulties in grasping or reaching actions [10], [11].

This division suggests that these two streams process and transform the visual information specifically for these two different uses. It is noted that the level of dissociation between the Ventral and Dorsal Streams is not yet clear, with other interpretations suggesting more complex interconnections [12], [13]. However, despite these debates, it is clear that there is some division, and that there exists different neuronal representations of visual information based on their neurophysiological location and associated functions.

For the purpose of goal-orientated rehabilitative exercise, it is clear that the action-related visual stream is of most interest. As such, the focus for the remainder of this section focuses on the PPC, which is dedicated to the online visual evaluation (*moment-to-moment information*) and online driving of goal-directed actions (*vision-for-action*) [14].

B. Spatial Representations for Action

There is significant evidence to suggest that within the PPC, the body and the environment are represented in an egocentric coordinate system. That is, the positions of the target location and the moving body part are represented relative to the body.

Buneo et al. recorded brain activity during reaching experiments with monkeys, and used this to show that both hand and object (*i.e.* target) locations are encoded in an eye coordinate system, and that this common coordinate system allows for movement planning to be performed by simply substracting one from the other [15]. This suggests a direct, egocentric representation of locations used to perform hand movements. Flanders and Soechting [16] proposed a similar conclusion, suggesting that the frame of reference in which we sense motion reflects a compromise among several representations issued from various sensors (*e.g.* the vestibular system, vision or muscle stretch) leading to a body-related representation.

Additionally, experiments with macaques show that neurons of the superior temporal sulcus are selectively sensitive to external movements but not to limb self-motion [17]. This is potentially of importance, suggesting that different areas can be recruited for direct visuomotor exercise (involving limb self motion towards a target) than for an indirect one where the self-motion may be kept out of the visual field and dissociated from the 'movement' and the 'target' represented on a screen (see II).

Finally, evidence for this egocentric representation is also evident in experiments involving patients with neurological injury. A subject with visual agnosia (legion within the VS) demonstrated better performance in perception and action tasks when these were egocentric than allocentric [18]. This again suggests that, especially within the DS responsible for feedback in goal-orientated actions, egocentric representations are likely to be used.

IV. The Neurorehabilitation Perspective

Neurological lesions may lead to a broad variety of deficits, as emphasised in the previous section, including motor, perception and sensory disorders, and their combination at various levels. Rehabilitation of people with neurological deficits such as stroke aims to improve patients' functional capabilities, both by stimulating true recovery through relearning as well as by training functional compensatory strategies. Even within the restricted scope of recovery of upper-limb motor functions, many different approaches exist to respond to the variety of patient presentations.

A. Visuomotor Feedback in Traditional Neurorehabilitation

Traditional neurorehabilitation techniques include those that involve direct feedback, but a number of techniques use modified visual feedback, including indirect. One such technique is mirror therapy, which involves placing a mirror in the midsagittal plane in order to reflect the movements of the non-paretic limb. This provides the illusion of non-impaired movements of the paretic side. The latest Cochrane review on the subject [19], indicates effectiveness of therapy to improve motor function but no clear evidence in treatment of visuospatial neglect. Visuospatial neglect, a syndrome in which the patient fails to attend to or respond to visual stimuli presented on the contralateral side, is of particular interest here and benefits from specifically targeted therapies. The Prism Adaptation intervention is the most commonly employed of these and appears to be the most effective, even if generalisation to post-intervention is limited [20]. This therapy uses a distortion of the visual perception which is different again from the indirect visual feedback previously mentioned. Another contemporary strategy that builds on mirror therapy is Graded Motor Imagery (GMI). This multi-stage intervention also uses indirect visual feedback through mirror therapy, laterality and mental visualisation [21]. Nevertheless, although impairment specific therapies exist, most neurological events impact several areas and thus lead to several intricated deficits. It has been recently shown for example that visuospatial neglect and kinesthesic deficit are highly intricated in stroke patients [22], suggesting the importance of accounting for both aspects in therapies.

Besides practice driven by the specificity of the impairment, traditional neurorehabilitation of the upper-limb relies mostly on repetitive goal-orientated practice with only slight differences in approaches from Conventional — which includes strengthening, teaching of compensatory strategies and functional practice — to Bobath — focusing on reducing pathological synergies — or Constraint Induced Motion Therapy (CIMT) — which enforces functional practice [1]. These practices, besides their differences, are all based on movement repetitions practiced with a direct, non-modified, visual feedback for the patient.

B. The Shift of Virtual Rehabilitation

Since the 1970s interactive systems and robotic devices has been progressively introduced into neurorehabilitation practices. Although their penetration is still limited today, a number of commercial devices are available, and their use is now part of standard practice. The promise of such devices is to enable an increase in practice intensity by better motivating and engaging the patients through gamification, and by reducing the therapist's physical burden of supporting the patient's limb.

Robotic therapy has since been shown to be potentially as good as traditional practice [23], [24] — even if questions remain due to the variability of devices and evaluation protocols. But it is important to note that most of these devices, in order to gamify the exercises, are replacing the direct visual feedback used in traditional physiotherapy and occupational therapy with an indirect one, provided over a computer screen, as illustrated on Figure 2.

(a) InMotionArm

(b) M2

(c) ArmeoPower

(d) Pablo

Fig. 2: Examples of commercial robotic devices using an indirect visual feedback: The InMotionArm (Bionik Laboratories, Toronto, Canada), the M2 (Fourier Intelligence, Shanghai, China), the ArmeoPower (Hocoma, Volketswil, Switzerland) and an interactive device: the Pablo (Tyromotion, Graz, Austria).

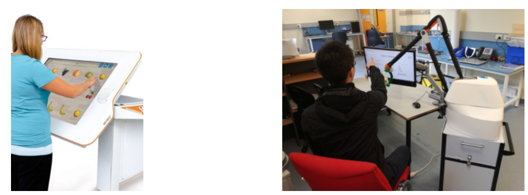

Fig. 3: Examples of one passive device, the Myro (Tyromotion, Graz, Austria) and one robotic device, the EMU [25] with direct visual feedback.

Besides a few systems using a direct visual feedback such as the EMU [25] (developed by the authors) or the Tyromotion Myro using touch screens (see Figure 3) and devices using Head Mounted Displays (HMD), all devices act as a joystick, driven by or with the patient's arm, which in turn controls a cursor on a screen placed vertically in front of them. This setup is similar to a standard joystick for video games or a mouse for a computer. Thus the space within which the practice movement is performed and the kinesthesic feedback provided — often in a transverse or sagittal plane — is decoupled from the space where the movement is perceived by the visuomotor system — a vertical screen. That is, exercising with these devices enforces the use of unaligned, indirect feedback.

V. Discussion

When neurologically impaired subjects are treated for motor control loss and not specifically for a vision, sensory or perception related one, no specific practice is often used. The main practice consists of mass repetitions, which is traditionally performed with direct visual feedback. However, the use of indirect feedback is increasing due to the adoption of technological aids. It has been shown that goal-orientated tasks are more difficult to perform under indirect feedback (see Section II). The cause of this may be related to the egocentric spatial representation used within the Dorsal Stream. This in itself does not necessarily reduce the effectiveness of the rehabilitative exercise, but may affect the instantaneous training difficulty and thus the patients motivation (negating one of the primary purposes of using technology — increasing engagement). Such issues may be addressed through simplification of the games and actions, but this may reduce the complexity of the exercise and thus its relevance to activities of daily living. It would be thus interesting to investigate the impact of indirect feedback on instantaneous motor performance of individuals, subject to the use of these new rehabilitation practices.

Nevertheless, the literature does suggest that motor adaptation and learning can transfer from training with indirect feedback to direct feedback. It is not clear, however, the degree to which this transfer occurs, how this compares to training exclusively with direct feedback, and whether this relationship carries over to matters of neurological recovery. This is further complicated due to the evidence that the Dorsal and Ventral Streams have different neurophysiological locations, and the possibility that indirect and direct feedback may involve the use of different brain areas. Exercises using a certain type of feedback may thus inadvertently train an area which is not directly affected by the injury (and thus is of less interest to train). Additional studies on transfer — and generalisation — of training performed with indirect visual feedback should thus be carried out, with a particular attention to the brain lesion area.

VI. Conclusion

There is no strong evidence that either direct or indirect feedback is preferable within a neurorehabilitation context. However, the literature demonstrates that there is a difference in task performance depending on the feedback, and that it is likely that slightly different neural pathways are stimulated in the execution of these tasks. Although most technological aides use indirect feedback, it is clearly technically feasible to instead use direct feedback. As such, despite the challenges with investigating efficacy in neurorehabilitation, it is suggested that the effects of direct feedback are more thoroughly studied.

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