CHAPTER

Eye-hand re-coordination: A pilot investigation of gaze and reach biofeedback in chronic stroke

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Abstract

Within the domain of motor performance, eye-hand coordination centers on close relationships between visuo-perceptual, ocular and appendicular motor systems. This coordination is critically dependent on a cycle of feedforward predictions and feedback-based corrective mechanisms. While intrinsic feedback harnesses naturally available movement-dependent sensory channels to modify movement errors, extrinsic feedback may be provided synthetically by a third party for further supplementation. Extrinsic feedback has been robustly explored in hand-focused, motor control studies, such as through computer-based visual displays, highlighting the spatial errors of reaches. Similar attempts have never been tested for spatial errors related to eye movements, despite the potential to alter ocular motor performance. Stroke creates motor planning deficits, resulting in the inability to generate predictions of motor performance. In this study involving visually guided pointing, we use an interactive computer display to provide extrinsic feedback of hand endpoint errors in an initial baseline experiment (pre-) and then feedback of both eye and hand errors in a second experiment (post-) to chronic stroke participants following each reach trial. We tested the hypothesis that extrinsic feedback of eye and hand would improve predictions and therefore feedforward control. We noted this improvement through gains in the spatial and temporal aspects of eye-hand coordination or an improvement in the decoupling noted as incoordination post-stroke in previous

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studies, returning performance toward healthy, control behavior. More specifically, results show that stroke participants, following the interventional feedback for eye and hand, improved both their accuracy and timing. This was evident through a temporal re-synchronization between eyes and hands, improving correlations between movement timing, as well as reducing the overall time interval (delay) between effectors. These experiments provide a strong indication that an extrinsic feedback intervention at appropriate therapeutic doses may improve eye-hand coordination during stroke rehabilitation.

Keywords

Coordination, Eye, Hand, Stroke, Biofeedback, Re-coordination

1 Introduction

Eye-hand coordination (EHC) depends critically on integrated control of ocular and appendicular sensorimotor systems to accomplish a single goal, such as touching a visual target. Optimal coordination between eye and hand relies on complex feedforward- and feedback-mediated relationships between the visuo-perceptual, ocular and appendicular motor systems, and takes advantage of finely orchestrated synergies between these systems in both the spatial and temporal domains.

Feedforward control is the prediction, planning and subsequent generation of motor commands based on a desired action. Feedback control corrects these commands based on sensory feedback about motor performance, involving error detection and modification either in real-time during the movement (online correction) or following movement termination (offline modification of future movement (Ao et al., 2015)). Feedback derived from motor errors can be classified as either "intrinsic" or "extrinsic." Intrinsic feedback refers to innate sensory-perceptual information channels that monitor motor performance as judged against desired performance through both comparisons to efference copy and the motor execution compared to the external environment (Sigrist et al., 2013). Intrinsic feedback is what is naturally available. Extrinsic feedback, in contrast, is provided synthetically by a third party or external device to supplement intrinsic feedback. Extrinsic feedback may be leveraged experimentally, typically by enhancing the information provided visually (screens), aurally (speaker, headphones), tactilely (robots, vibrotactile), or a combination of the above (Sigrist et al., 2013).

Evidence-based clinical practice guidelines for post-stroke rehabilitation include biofeedback (extrinsic feedback) as a favorable management recommendation for several post-stroke conditions, including impairments of gait, balance, and motor control (Panel, 2006). While biofeedback has been implemented with success often through visual cues and prompts in stroke rehabilitation, these approaches very often center on correcting the hand/limb component of the intended action. This continues in contemporary rehabilitation despite the fact that most tasks and interventions are visually guided actions that require eye-hand coordination (Seok et al., 2016), and it

assumes that no inherent dysfunction resides on the visual system or in integrating the visual and motor components for coordinated control. Predicting the consequence of a motor plan and any anticipated error is the essence of feedforward control (Wolpert and Ghahramani, 2000; Wolpert et al., 1995); this is true for movement in the hand and also the eye. Improving these predictions should allow one to improve motor performance through the process of motor learning (Shadmehr and Wise, 2005). In stroke, there are motor planning deficits, as hemiparetic patients are unable to properly predict the impact of a given set of neural commands when asked to perform visually guided hand movements (Beer et al., 1999). If these predictions are impaired, external "prompts" or visual cues may help adjust not only hand control, but also eye control and inform a working eye-hand coordination model.

In our study, we provide extrinsic feedback as part of a visually guided pointing task that is focused on remediating eye-hand incoordination, defined as temporal decoupling of eye and hand during attempted coordination, for participants with middle cerebral artery stroke. Separate feedback signals convey, first, the difference between the actual endpoint of the saccade and the intended spatial target, and second, the actual endpoint of the reach. We test the hypothesis that adaptive control mechanisms will be recruited to rescue both temporal and spatial aspects of eye-hand decoupling in these stroke subjects, guiding performance toward neurotypical coupling (normative eye-hand control).

2 Methods

2.1 Subjects

Seventeen (17) neurologically sound control subjects (aged 26.2 ± 4.6) and 13 stroke participants (57.4 ± 14.2) with a known history of middle cerebral artery ischemic stroke were recruited. Among the stroke participants, seven had right hemispheric middle cerebral artery (MCA) stroke and six had left hemispheric MCA strokes (mild-moderate motor impairment [Fugl-Meyer Scale]; <2 modified Ashworth scale). The clinical characteristics of the stroke participants are summarized in Table 1.

2.2 Inclusion and exclusion criteria

A focused stroke history and neurological and musculoskeletal examinations (inclusive of more extensive range of motion analyses) were performed on all participants to determine inclusion/exclusion.

Stroke participants: (1) ≥ 18 years, (2) injury in the in the middle cerebral artery (MCA) distribution at least 4 months prior to enrollment, (3) ability to complete the Fugl-Meyer Score (FMS) to define arm motor impairment (Fugl-Meyer et al., 1975), (4) a full range of eye movements in horizontal and vertical directions, as assessed by the experimenter, (5) ability to perform pointing tasks, as assessed by the

Table 1 Clinical characteristics of stroke participants.

Subject ID	Age (Years)	Sex	Stroke characteristics[a]	Chronicity (Months)	Fugl-Meyer score[b]
1	78	M	R MCA distribution	24	66
2	61	F	R MCA distribution	84	66
10	39	M	R MCA distribution	55	47
11	70	M	R MCA distribution	2	66
6	60	F	R MCA distribution	30	30
7	73	M	R MCA distribution	72	58
8	51	F	R MCA distribution	146	30
3	34	M	L MCA distribution	19	66
4	39	F	L MCA distribution	16	45
5	70	M	L MCA distribution	32	58
9	60	M	L MCA distribution	52	63
12	47	F	L MCA distribution	17	61
13	65	F	L MCA distribution	7	66
Avg. (SD)	57.5 (14.3)			42 (39)	55.5 (13.3)

[a]*Stroke characteristics, lesion location obtained from medical history with participant and/or family members serving as historian; region and laterality cross-validated for consistency with examination findings.*
[b]*Fugl-Meyer Score, a summation of the Upper Extremity Score (out of 66), which reflects the extent of post stroke motor impairment.*

experimenter, (6) willingness to complete all clinical assessments, and (7) an ability to give informed consent and complete HIPPA certifications.

Control and stroke participants were excluded if they met any of the following criteria: (1) cognitive dysfunction <24 on the Mini Mental Status (Srivastava et al., 2006), (2) significant injury to an eye, weakness in extraocular muscles or presence of visual field cuts, assessed by the Beery-Buktenica Developmental Test of Visual-Motor Integration (Beery VMI) (Malloy et al., 2003; Temple et al., 2010; Zagar and Mead, 1983), standard clinical tests for visual acuity (Snellen chart) (Tannenbaum, 1971), visual fields (Beck et al., 1985). The 25-item National Eye Institute Visual Functioning Questionnaire and a 10-item neuro-ophthalmic supplement survey were completed to quantify the extent of disability due to perceived visual deficits (Beck et al., 1985), (3) hemi-spatial neglect assessed via the line bisection test (Schenkenberg et al., 1980) and the single-letter cancellation (Johnston and Diller, 1986), (4) major disability, as determined by a score >4 on the modified Rankin scale (Johnston and Diller, 1986; Rankin, 1957), (5) previous neurological illness, confounding medical conditions, or significant injury to the upper extremity, (6) significant depression determined by a score <11 on the Geriatric Depression scale (Volz et al., 2016), (7) pregnancy, and (8) electrical implant devices, e.g., pacemakers or defibrillators.

A video eye tracker (Eye Link ll) was used to record eye movements. Subjects were seated on an adjustable chair 60 cm away from Dell 27″ monitor screen. The eye tracker was calibrated for each participant before each session. A motion sensor (Polhemus) was affixed to the distal aspect of the index finger of the hand on the to-be-tested arm (the dominant arm for controls, and both arms in participants with stroke). The Polhemus sensor was affixed to the finger by first placing it on the finger and securing it at three locations (proximal and distal phalanx and wrist). A nine-point grid on the table top spanning 12 by 9 cm was used to calibrate the Polhemus sensor. At the beginning of each trial participants were asked to place their sensor-attached fingertip at known locations on the table to calibrate the fingertip to the table.

2.3 Experiment

To assess potential learning effects secondary to the addition of extrinsic feedback focused on ocular motor errors, subjects participated in two experiments involving a pro-saccade look-and-reach task. The first experiment included terminal error feedback of hand position (baseline) and the second experiment (feedback) included extrinsic feedback of reach and ocular motor error (LeVasseur et al., 2001).

In each experiment, controls participated in one session, and stroke participants completed up to two sessions, one per arm (depending on whether they were capable). During each session, a subject made 152 reaches; 76 to a randomly selected sequence of five target locations on a circle centered on the start position of the reach, and 76 starting from a separate randomly selected sequence of the same target circles to the center of the circle (center-out and center-in reaches did not show substantial differences and data were collapsed across these conditions in the analysis). At the beginning of each session, participants were instructed in the task, and it was verified that they understood the task and could execute the required reaches by performing a short series of familiarization trials. Familiarization concluded when subjects had learned to make the basic movement by responding to visually presented targets and go-beeps (see below). Each reach was accomplished by lifting the motion-sensor attached index finger, and only re-touching the table at movement termination (rather than sliding the finger or a stylus across the table). They were additionally instructed to minimize head motion by maintaining a stable (aligned) head/neck posture.

At the start of each trial, participants maintained fixation at a visual indicator (blue "start circle"). In half of each session (76 reaches) the movement began at the screen center toward a peripheral target, and in half of trials movements started at a peripheral position and progressed toward the screen center. The movement target (a small white circle, approx. 0.5° visual angle) was illuminated for 0.5 s, and the look-and-reach movement was cued by the simultaneous presentation of a "GO" beep and extinguishing of the start circle. Participants were instructed to move their eyes and finger as quickly and accurately as possible to the target position on the table. Participants were given feedback at the end of each movement. Feedback of fingertip endpoints was displayed at reach termination in both experiments,

and eye error feedback was displayed at the end of the reach in the feedback experiment. Eye feedback was shown on the screen at the spatial location recorded at the time of peak fingertip velocity, when in healthy controls the eye has typically fixated the target (Hayhoe et al., 2012) [to reinforce the coupling between eye and hand]. The experiment was performed with both hands (one session per hand) in participants with stroke whenever possible. Incomplete or drop-out participant-related data was excluded.

This study was approved by the Institutional Review Board of New York University's School of Medicine. Written informed consent was obtained from all participants.

2.4 Statistical analysis

Data were first median-filtered to remove outliers, and kinematic parameters were estimated after individual trials were aligned to the time of reach onset. Velocity traces were unremarkable and were not studied further. Two-sample *t*-tests were used to compare pairs of means. The results were compared with Welch's *t*-test due to unequal sample sizes and likely heteroscedasticity. As an adjunct to traditional *t*-tests, Bayesian analogues of the reported *t*-tests confirm our statistical results; 95% Bayesian confidence regions around all computed estimates, shown in the figures, display the result of the comparison graphically.

2.5 Results

2.5.1 Demographics

The participants with stroke were uniform in their neuroanatomic injury patterns; a full list of clinical characteristics is presented in Table 1. The mean FMS (Fugl-Meyer Score) was 55.5 ± 13.3, with a range of 30–66.

3 Eye and hand movement timing/duration

The primary saccade produced by stroke participants during the baseline experiment occurred significantly earlier than in healthy participants regardless of the examined limb. As described previously, these early saccades are likely due to a disinhibition process that likely includes an anticipatory component (Rizzo et al., 2017b). In the second experiment with ocular motor feedback, stroke participants still initiated saccades early compared to controls, but later relative to their own baseline. However control participants began making premature saccades (early) when compared to their baseline data (basline experiment control: 529 ms, CI[520 537], less-affected arm: 106 ms CI[80 132]; more-affected arm: 82 ms, CI[52 112]; feedback experiment control: 445 ms CI[434 456], less affected 118 ms CI[82 154], more affected 172 ms CI[130 215]. Stroke participants also reversed the trend in their reaching behavior and initiated reaches earlier in both the less- and more-affected arm, while reach

initiation in controls was similar in both experiments (baseline: control: 566 ms, CI[555–577], less-affected arm: 545 ms CI[521 568]; more-affected arm: 600 ms, CI[569631]; feedback: control: 566 ms CL[555 577], less affected 466 ms CI[439 494], more affected 558 ms CI[542 575]. We define the time interval between the primary saccade and reach onset as our measure of temporal decoupling; this was significantly longer in stroke participants compared to controls in both experiments (baseline control: 26.8 ms CI[16.3 37.4], less affected: 439 ms CI[404 474], more affected: 519 ms CI[476 562]). During the experiment with extrinsic feedback, primary saccades were "re-coordinated" or re-coupled in stroke participants, reducing the time between saccade onset and reach onset and more closely approximating control behavior, re-synchronizing effectors (control: 121 ms CI[105 136], less affected: 348 ms CI[303 394], more affected: 386 ms CI[341 431]). In addition, correlations between saccade and reach onsets for individual reaches across all participants were significantly lower in stroke participants in the baseline experiment (control: $r = 0.63$ CI[0.6 0.65], less affected: $r = 0.36$ CI[0.31 0.41], more affected: $r = 0.31$ CI[0.25 0.37]), but were nearly identical in the feedback experiment (control: $r = 0.42$ CI[0.39 0.45], less affected: $r = 0.42$ CI[0.34 0.49], more affected: $r = 0.41$ CI[0.33 0.49]) (Fig. 1).

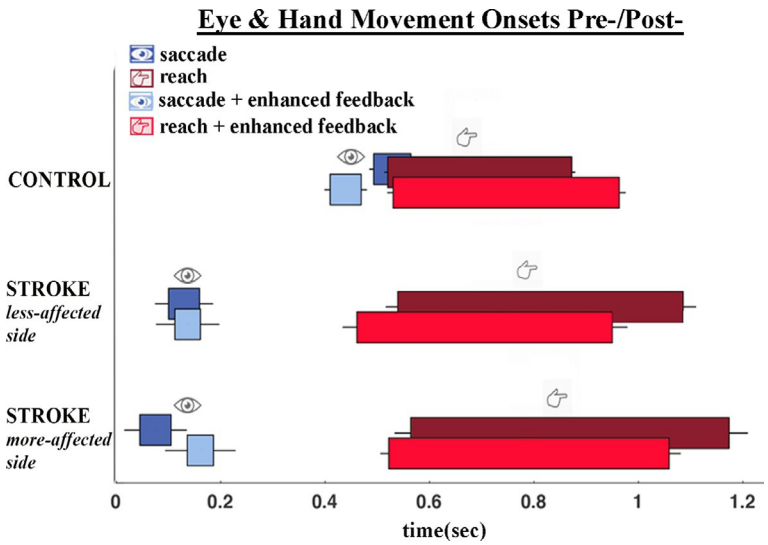

FIG. 1

Eye and hand movement onsets pre-/post-: Movement onset and offset (termination) times for the eye (blue) and hand (red), as represented by the left and right edges of the corresponding bars. Movement onsets/offsets between eye (saccade) and hand (reach) are compared pre-/post- (darker to lighter color) "enhanced feedback" (extrinsic feedback of the eye and hand) for controls, and both more- and less-affected arms in stroke participants.

Participants with stroke typically manifest with prolonged reach durations; during baseline performance, durations were indeed longer, as compared to controls, in addition to the degree of prolongation correlating to arm motor impairment severity. By comparison, at the end of the feedback experiment, reach duration decreased on average in stroke participants in both the less (from 546 s CI[537 555] to 486 ms CI [477 495]) and more affected limbs (from 604 ms CI[587 622] to 537 ms CI[522 552]), while control participants made significantly longer reaches (from 352 ms CI[348 356] to 433 ms CI[428 438]). Saccade duration was significantly shorter in stroke participants, as compared to control participants in both experiments (baseline, control: 71.2 ms CI[70.2 72.2], less affected: 59.3 CI[58.0 60.4], more affected: 59.9 CI[58.7 61.0]; feedback, control: 59.1 ms CI[57.7 60.6], less affected: 48.4 CI [46.9 49.8], more affected: 49.8 CI[48.3 51.3]; Fig. 2), which corresponds to saccades that are usually about 10 mm. shorter in patients than controls (control baseline: 59.0 mm CI[58.6 59.5], feedback: 64.3 mm CI[63.9 64.6]; less affected baseline: 54.4 CI[53.7 55.1], feedback: 53.4 CI[52.4 54.4]; more affected baseline: 51.4 CI[50.7 52.1], feedback: 53.9 CI[53.0 54.8]).

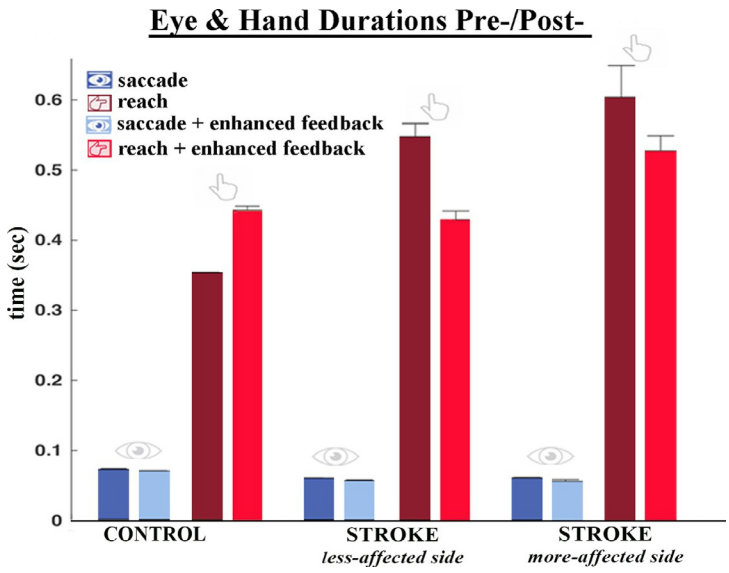

FIG. 2

Eye and hand durations pre-/post-: Movement durations for the eye (blue) and hand (red), as represented by top edge of the corresponding bars. Movement durations between eye (saccade) and hand (reach) are compared pre-/post- (darker to lighter color) "enhanced feedback" (extrinsic feedback of the eye and hand) for controls, and both more- and less-affected arms in stroke participants.

4 Spatial errors for look and reach

Fig. 3 demonstrates that spatial errors (endpoint distance from the target) decreased after feedback was provided to participants. Endpoint reach errors decreased in control and stroke participants regardless of reaching limb. The accuracy improvement was significant in controls and the more affected arm of stroke participants (baseline experiment: control 9.3 mm, less affected 19.2 mm, and more affected 21.4 mm; feedback: control 6.9 mm, less affected 17.4 mm and more affected 14.6 mm). Interestingly, we also provide evidence that the spatial error of primary saccades improved post-feedback, on average, in the stroke condition, across both arms; this was not the case in controls. The concordance between eye and hand gains in spatial errors is of particular interest and contrary to findings in controls. Remarkably, as noted above, while controls de-synchronize eye and hand movement timing when provided extrinsic eye and hand feedback, stroke participants appear to benefit and re-synchronize, pairing robustly with the concordant spatial gains.

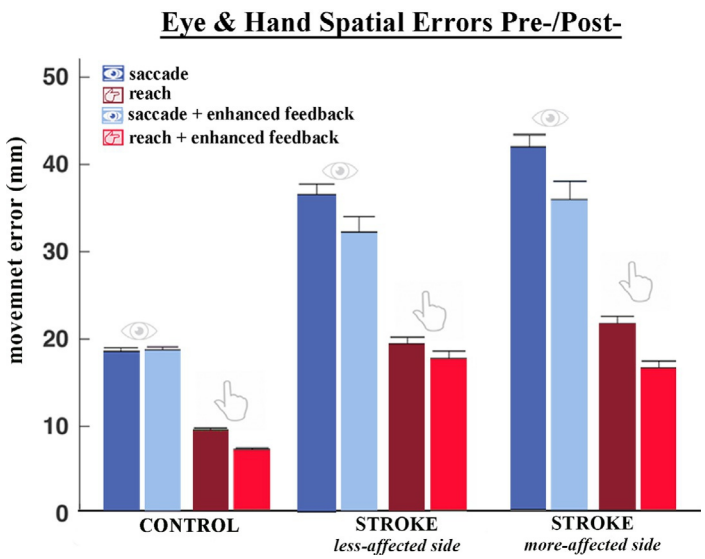

FIG. 3

Eye and hand spatial errors pre-/post-: Spatial errors for the eye (blue) and hand (red), as represented by top edge of the corresponding bars. Spatial errors between eye (saccade) and hand (reach) are compared pre-/post- (darker to lighter color) "enhanced feedback" (extrinsic feedback of the eye and hand) for controls, and both more- and less-affected arms in stroke participants.

5 Discussion

In the present study, corrective mechanisms were recruited to rescue and re-coordinate eye-hand coupling in stroke participants, guiding performance back toward neurotypical coupling through extrinsic feedback that includes endpoint errors of both saccades and reaches. This was evident through gains in temporal resynchronization, spatial accuracy, shorter reach durations, and improved onset correlations between effectors.

Stroke patients often suffer from deficits that affect their ability to make proper use of sensory information (intrinsic feedback) above and beyond their motor deficits (Ward and Cohen, 2004). Their impairments are often noted during dynamic eye-hand coordination tasks, emphasizing potential difficulties in rapidly processing sensory information, as well as in sensorimotor planning, integration, and motor execution. Inefficient handling of sensory information may lead to difficulties in predicting target motion, a deficit in feedforward mechanisms, and in the integration of sensory feedback for error correction (Caeyenberghs et al., 2009, 2010). In fact, predictive control is vital to optimized visuomotor planning (Hudson et al., 2008). Sensorimotor impairment may be multifactorial and compromised secondary to not only ocular motor deficits but also visuospatial planning and visuoperceptual abnormalities (Kaplan and Hier, 1982; Machner et al., 2009; Malhotra et al., 2006; Mennem et al., 2012; Rowe et al., 2009). As described previously, early primary saccades elicited by stroke participants, likely due to a reflexive, upper motor neuron-like disinhibition, may be triggered as an attempt to anticipate spatial targets in time and space (Rizzo et al., 2017b). While this evidence alone, is enough to suggest that related predictions for ocular motor control are likely poor, recent results also support that eye-hand tasks are significantly decoupled in time for both the more and less affected hands, and for targets in either hemifield. In addition to expected reach errors for the hemiparetic limb, there are also spatial errors noted for saccades, in otherwise visually intact participants (Rizzo et al., 2017a).

Feedback delivered extrinsically has been demonstrated to improve the effect of upper limb training in stroke patients (Subramanian et al., 2010). By providing this information explicitly (on-screen) at the end of each reach, an external, synthetic information source is able supplement natural, intrinsic feedback signals that underlie normal adaptation and learning mechanisms (Huang et al., 2005; Kim et al., 2015). Error biofeedback of the limb has been studied extensively (Alhasan et al., 2017; Huang et al., 2005; Urra et al., 2015; Van Dijk et al., 2005), but error biofeedback of the ocular motor system is a plausible, yet previously untested, concept in which primary saccadic endpoints (offline) are displayed on-screen relative to the intended spatial target. In stroke, where disinhibition has been noted in the ocular motor system, eye movements may be prematurely initiated with compromised accuracy (Rizzo et al., 2017b). Providing saccade error feedback may re-focus stroke

participants on eye movement control, while reducing the cognitive/computational demands associated with the corrective actions necessary to improve that control. Improving the accuracy and timing of fixations will in turn improve the quality of visual information available for reach control, ultimately improving overall performance.

These results are consistent with previous studies suggesting that performance feedback may facilitate the neural processing required for motor-error correction and improve the feedforward predictions of motor commands. In stroke participants, extrinsic feedback helps improve reach outcomes, including spatial and temporal errors (Cirstea and Levin, 2007; Maulucci and Eckhouse, 2001; Simonsen et al., 2017). In contrast to a previous study showing longer movement durations following feedback, stroke participants in our study made shorter duration reach movements in the feedback experiment when compared to the baseline experiment (Simonsen et al., 2017). In contrast, studies have shown that visual feedback can be unfavorable for visuomotor adaptation in healthy participants (Sigrist et al., 2013), which is consistent with a trend toward decoupling in our control participants.

Our study evaluated the effect of externally provided, terminal saccade feedback on a relatively simple look-to-reach task that aims to aid eye-hand incoordination. The effectiveness of extrinsic feedback was previously shown to vary based on task complexity and feedback timing (Winstein, 1991; Wulf and Shea, 2002). Studies have also been performed using different types of extrinsic feedback including visual, auditory, haptic, and multimodal; there is no consensus regarding the most effective way to provide such feedback (Sigrist et al., 2013). We believe visual feedback through extrinsic spatial prompting served here to improve eye movement accuracy, adding an emphasis on eye movement control, both of which served to help re-balance the cognitive resources and ultimately central control required to orchestrate eye-hand function post-injury.

Visually guided reaching relies on a constellation of processing resources, including both working memory and executive function (Baddeley, 2003; Baddeley and Hitch, 1974). It is likely that either the use of these resources, their full extent, or both may be impaired following stroke. A source of extrinsic feedback such as the one provided in our feedback experiment may provide error information (or may emphasize error information) that is not fully coded or processed following stroke. When provided with the means to reduce cognitive load in this way, our stroke participants showed evidence of enhanced eye/hand temporal coupling and overall error correction. Future studies should manipulate the complexity of the task, timing of feedback, and different feedback modalities to determine the appropriate dosing, frequency, and detailed form of feedback to optimize therapeutic outcomes. Our results provide a strong indication that employing extrinsic feedback in appropriate therapeutic doses may significantly improve ocular motor capabilities in the setting of eye-hand coordination for stroke rehabilitation.

References

Alhasan, H., Hood, V., Mainwaring, 2017. The effect of visual biofeedback on balance in elderly population: a systematic review. Clin. Intervent. Aging 12, 487.

Ao, D., Song, R., Tong, K.-Y., 2015. Sensorimotor control of tracking movements at various speeds for stroke patients as well as age-matched and young healthy subjects. PLoS One 10, e0128328.

Baddeley, A., 2003. Working memory: looking back and looking forward. Nat. Rev. Neurosci. 4, 829–839.

Baddeley, A.D., Hitch, G., 1974. Working Memory. Psychology of Learning and Motivation. Elsevier.

Beck, R.W., Bergstrom, T.J., Lighter, P.R., 1985. A clinical comparison of visual field testing with a new automated perimeter, the Humphrey field analyzer, and the Goldmann perimeter. Ophthalmology 92, 77–82.

Beer, R., Dewald, J., Rymer, Z., 1999. Disturbances of voluntary movement coordination in stroke: problems of planning or execution? Prog. Brain Res. 123, 455–460.

Caeyenberghs, K., Van Roon, D., Van Aken, K., De Cock, P., Linden, C.V., Swinnen, S.P., Smits-Engelsman, B.C., 2009. Static and dynamic visuomotor task performance in children with acquired brain injury: predictive control deficits under increased temporal pressure. J. Head Trauma Rehabil. 24, 363–373.

Caeyenberghs, K., Leemans, A., Geurts, M., Taymans, T., Vander Linden, C., Smits-Engelsman, B.C., Sunaert, S., Swinnen, S.P., 2010. Brain-behavior relationships in young traumatic brain injury patients: fractional anisotropy measures are highly correlated with dynamic visuomotor tracking performance. Neuropsychologia 48, 1472–1482.

Cirstea, M.C., Levin, M.F., 2007. Improvement of arm movement patterns and endpoint control depends on type of feedback during practice in stroke survivors. Neurorehabil. Neural Repair 21, 398–411.

Fugl-Meyer, A.R., Jaasko, L., Leyman, I., Olsson, S., Steglind, S., 1975. The post-stroke hemiplegic patient. 1. A method for evaluation of physical performance. Scand. J. Rehabil. Med. 7, 13–31.

Hayhoe, M.M., McKinney, T., Chajka, K., Pelz, J.B., 2012. Predictive eye movements in natural vision. Exp. Brain Res. 217, 125–136.

Huang, H., Ingalls, T., Olson, L., Ganley, K., Rikakis, T., He, J., 2005. Interactive multimodal biofeedback for task-oriented neural rehabilitation. Conf. Proc. IEEE Eng. Med. Biol. Soc. 3, 2547–2550.

Hudson, T.E., Maloney, L.T., Landy, M.S., 2008. Optimal compensation for temporal uncertainty in movement planning. PLoS Biol. 4, e1000130.

Johnston, C.W., Diller, L., 1986. Exploratory eye movements and visual hemi-neglect. J. Clin. Exp. Neuropsychol. 8, 93–101.

Kaplan, J., Hier, D.B., 1982. Visuospatial deficits after right hemisphere stroke. Am. J. Occup. Ther. 36, 314–321.

Kim, C.Y., Lee, J.S., Lee, J.H., Kim, Y.G., Shin, A.R., Shim, Y.H., Ha, H.K., 2015. Effect of spatial target reaching training based on visual biofeedback on the upper extremity function of hemiplegic stroke patients. J. Phys. Ther. Sci. 27, 1091–1096.

LeVasseur, A.L., Flanagan, J.R., Riopelle, R.J., Munoz, D.P., 2001. Control of volitional and reflexive saccades in Tourette's syndrome. Brain 124, 2045–2058.

Machner, B., Sprenger, A., Kompf, D., Sander, T., Heide, W., Kimmig, H., Helmchen, C., 2009. Visual search disorders beyond pure sensory failure in patients with acute homonymous visual field defects. Neuropsychologia 47, 2704–2711.

Malhotra, P., Coulthard, E., Husain, M., 2006. Hemispatial neglect, balance and eye-movement control. Curr. Opin. Neurol. 19, 14–20.

Malloy, P., Belanger, H., Hall, S., Aloia, M., Salloway, S., 2003. Assessing visuoconstructional performance in AD, MCI and normal elderly using the beery visual-motor integration test. Clin. Neuropsychol. 17, 544–550.

Maulucci, R.A., Eckhouse, R.H., 2001. Retraining reaching in chronic stroke with real-time auditory feedback. NeuroRehabilitation 16, 171–182.

Mennem, T.A., Warren, M., Yuen, H.K., 2012. Preliminary validation of a vision-dependent activities of daily living instrument on adults with homonymous hemianopia. Am. J. Occup. Ther. 66, 478–482.

Panel, O., 2006. Ottawa panel evidence-based clinical practice guidelines for post-stroke rehabilitation. Top. Stroke Rehabil. 13, 1–269.

Rankin, J., 1957. Cerebral vascular accidents in patients over the age of 60. I. General considerations. Scott. Med. J. 2, 127–136.

Rizzo, J.R., Fung, J.K., Hosseini, M., Shafieesabet, A., Ahdoot, E., Pasculli, R.M., Rucker, J.C., Raghavan, P., Landy, M.S., Hudson, T.E., 2017a. Eye control deficits coupled to hand control deficits: eye-hand incoordination in chronic cerebral injury. Front. Neurol. 8, 330.

Rizzo, J.R., Hudson, T.E., Abdou, A., Lui, Y.W., Rucker, J.C., Raghavan, P., Landy, M.S., 2017b. Disrupted saccade control in chronic cerebral injury: upper motor neuron-like disinhibition in the ocular motor system. Front. Neurol. 8, 12.

Rowe, F., Brand, D., Jackson, C., Price, A., Walker, L., Harrison, S., Eccleston, C., Scott, C., Akerman, N., Dodridge, C., Howard, C., Shipman, T., Sperring, U., Macdiarmid, S., Freeman, C., 2009. Visual impairment following stroke: do stroke patients require vision assessment. Age Ageing 38, 188–193.

Schenkenberg, T., Bradford, D.C., Ajax, E.T., 1980. Line bisection and unilateral visual neglect in patients with neurologic impairment. Neurology 30, 509–517.

Seok, H., Lee, S.Y., Kim, J., Yeo, J., Kang, H., 2016. Can short-term constraint-induced movement therapy combined with visual biofeedback training improve hemiplegic upper limb function of subacute stroke patients? Ann. Rehabil. Med. 40, 998–1009.

Shadmehr, R., Wise, S.P., 2005. The Computational Neurobiology of Reaching and Pointing: A Foundation for Motor Learning. MIT Press.

Sigrist, R., Rauter, G., Riener, R., Wolf, P., 2013. Augmented visual, auditory, haptic, and multimodal feedback in motor learning: a review. Psychon. Bull. Rev. 20, 21–53.

Simonsen, D., Popovic, M.B., Spaich, E.G., Andersen, O.K., 2017. Design and test of a Microsoft Kinect-based system for delivering adaptive visual feedback to stroke patients during training of upper limb movement. Med. Biol. Eng. Comput. 55, 1927–1935.

Srivastava, A., Rapoport, M.J., Leach, L., Phillips, A., Shammi, P., Feinstein, A., 2006. The utility of the mini-mental status exam in older adults with traumatic brain injury. Brain Inj. 20, 1377–1382.

Subramanian, S.K., Massie, C.L., Malcolm, M.P., Levin, M.F., 2010. Does provision of extrinsic feedback result in improved motor learning in the upper limb poststroke? A systematic review of the evidence. Neurorehabil. Neural Repair 24, 113–124.

Tannenbaum, S., 1971. The eye chart and Dr. Snellen. J. Am. Optom. Assoc. 42, 89–90.

Temple, V., Drummond, C., Valiquette, S., Jozsvai, E., 2010. A comparison of intellectual assessments over video conferencing and in-person for individuals with ID: preliminary data. J. Intellect. Disabil. Res. 54, 573–577.

Urra, O., Casals, A., Jane, R., 2015. The impact of visual feedback on the motor control of the upper-limb. 2015, 3945–3948.

Van Dijk, H., Jannink, M.J., Hermens, H.J., 2005. Effect of augmented feedback on motor function of the affected upper extremity in rehabilitation patients: a systematic review of randomized controlled trials. J. Rehabil. Med. 37, 202–211.

Volz, M., Mobus, J., Letsch, C., Werheid, K., 2016. The influence of early depressive symptoms, social support and decreasing self-efficacy on depression 6 months post-stroke. J. Affect. Disord. 206, 252–255.

Ward, N.S., Cohen, L.G., 2004. Mechanisms underlying recovery of motor function after stroke. Arch. Neurol. 61, 1844–1848.

Winstein, C.J., 1991. Knowledge of results and motor learning—implications for physical therapy. Phys. Ther. 71, 140–149.

Wolpert, D.M., Ghahramani, Z., 2000. Computational principles of movement neuroscience. Nat. Neurosci. 3 (Suppl), 1212–1217.

Wolpert, D.M., Ghahramani, Z., Jordan, M.I., 1995. An internal model for sensorimotor integration. Science 269, 1880–1882.

Wulf, G., Shea, C.H., 2002. Principles derived from the study of simple skills do not generalize to complex skill learning. Psychon. Bull. Rev. 9, 185–211.

Zagar, R., Mead, J.D., 1983. Analysis of a short test battery for children. J. Clin. Psychol. 39, 590–597.

Further reading

Optican, L.M., 2005. Sensorimotor transformation for visually guided saccades. Ann. N. Y. Acad. Sci. 1039, 132–148.