Eye Gaze Patterns after Stroke: Correlates of a VR Action Execution and Observation Task

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ABSTRACT

The concept of a partially shared neural circuitry between action observation and action execution in healthy participants has been demonstrated through a number of studies. However, little research has been done in this regard utilizing eye movement metrics in rehabilitation contexts. In this study we approach action observation and action execution by combining a virtual environment and eye tracking technology. Participants consisted of stroke survivors, and were required to perform a simple reach-and-grab and place-and-release task with both their paretic and non-paretic arm. Results showed congruency in gaze metrics between action execution and action observation, for distribution and duration of gaze events. Furthermore, in action observation, longer smooth pursuit segments were detected when observing the representation of the paretic arm, thus providing evidence that the affected circuitry may be activated during observation of the simulated action. These results can lead to novel rehabilitation methods using virtual reality technology.

Categories and Subject Descriptors

J.3 **[Computer Applications]**: Life and Medical Sciences - health; K.4.2 **[Computers and Society]**: Social Issues - assistive technologies for persons with disabilities

General Terms

Measurement, Performance, Experimentation

Keywords

Action execution, action observation, eye gaze, stroke, virtual reality

1. INTRODUCTION

Stroke is one of the primary causes of permanent disability among the current population [6]. In this regard, rehabilitation of post-stroke patients presents a great and costly challenge, and the mechanisms underlying stroke recovery have yet to be fully understood. These mechanisms have been the focus of several functional neuroimaging and electrophysiological studies that showed the importance of brain plasticity in the recovery process of post-stroke patients [3,8]. Some approaches proposed the activation of mirror neurons for stroke rehabilitation, showing that observing behaviors performed by others (action observation) elicits motor activity in the brain of the observer similar to that which occurs when the individual plans his/her own actions (action execution) [7].

Through neuroimaging techniques, such as functional magnetic resonance imaging (fMRI), researchers have been able to locate specific areas of brain activation and determine the spatial and temporal congruency between observing, executing, and imagining actions. As a result, there is now a better understanding that the covert elements (attention, motor planning) of action execution, action observation and movement imagery share, at least to some extent, similar neural networks and mechanisms [2,4].

In addition to imaging techniques, one promising method of quantifying imagery and observation of goal-oriented actions is by measuring eye movements during these conditions, which can highlight the involvement of attention and cognitive processes [5]. In regards to healthy participants, studies have demonstrated that there is, in fact, congruency in gaze metrics (fixation duration and number of fixations) between action execution and action observation, supporting the idea that these processes have a partially shared neural network [1].

In this study we aim at validating these findings in stroke patients, by comparing gaze metrics in eye-controlled action execution and action observation with both the paretic and non-paretic arm. The eye gaze of participants is analyzed in tasks where they observe their paretic and non-paretic arms in a virtual environment while executing reaching and grasping actions, and when they control the virtual arm directly with their eye gaze. Under the assumption of interference between the neuronal circuits underlying execution and observation, we expect to detect some differences in the paretic vs. non-paretic arm conditions that may eventually be used for diagnostic and rehabilitation purposes.

In particular, we aim at verifying the following hypotheses:

a) the congruency in gaze metrics between action execution and action observation in stroke patients;

b) differences in gaze metrics in stroke patients during action observation using their paretic arm when compared to their non-paretic arm, due to the interference between action observation and action execution circuits;

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Figure 1. Experimental setup being used by a stroke patient, consisting of a monitor with an integrated eye tracker running a custom made virtual reality environment.

c) the presence or absence of differences in gaze metrics in stroke patients during eye-controlled action when comparing the paretic to their non-paretic arm, depending on whether the recruitment of the affected motor control areas occurs or not for this condition.

In order to verify these hypotheses, a series of experimental trials was conducted with stroke patients, using a virtual environment as stimulus and eye tracking technology for data acquisition.

2. METHODS

2.1 Participants

Ten stroke survivors (5 male, 5 female), with a mean age of 66.1 years (*SD* = 10.6 years) and a mean of 221.2 days after stroke (*SD* = 157.4 days), participated in the study. 7 patients suffered an ischemic stroke and 3 patients suffered an intra-cerebral hemorrhage. 4 patients had a left-sided lesion and 6 patients had a right-sided lesion. All the participants were naive to the system and hypotheses being tested. All of them supplied written informed consent prior to participation. The study was approved by the Ethical Committee of the Regional Health System of Madeira (SESARAM).

Table 1. Characteristics of the participants

	Age (years)	Lesion side	Lesion type	Days since stroke
Participant 1	54	Left	Hemorrhagic	34
Participant 2	78	Left	Hemorrhagic	202
Participant 3	68	Right	Ischemic	474
Participant 4	78	Right	Ischemic	293
Participant 5	79	Right	Hemorrhagic	209
Participant 6	60	Right	Ischemic	140
Participant 7	52	Left	Ischemic	80
Participant 8	56	Left	Ischemic	489
Participant 9	62	Right	Ischemic	80
Participant 10	74	Right	Ischemic	211

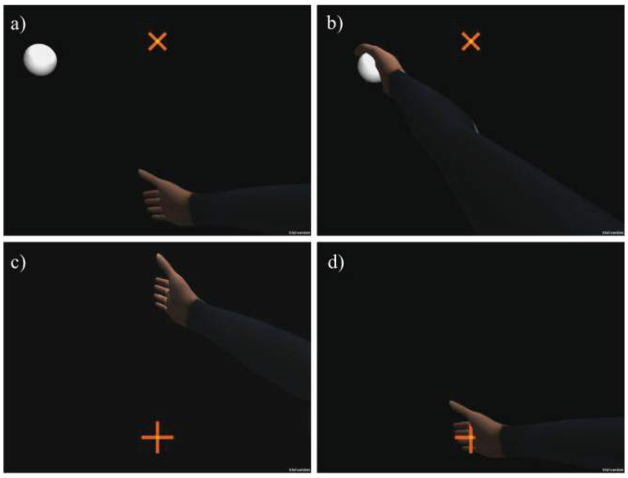

Figure 2. The virtual reality task consist of 4 steps: a) reaching and grasping of a virtual ball, b) placing it at the target, c) releasing it, and d) moving back to initial position.

2.2 System

For the purpose of this study, a custom virtual reality (VR) task was developed using the Unity 3D game engine (Unity Technologies, San Francisco, USA). The VR environment was displayed on a 4:3 monitor (1024 x 768 pixels resolution) with an integrated eye tracking system, the Tobii T120 Eye Tracker (Tobii Technology, Stockholm, Sweden). Eye movements were recorded at a sampling rate of 60 Hz. A laptop computer connected to the eye tracker ran the custom VR software during the trials.

Participants sat in front of the eye tracker, with their head at around 60 cm distance from the screen, and with both hands over the table in front of them. The VR environment, shown in the eye tracker display, presented the user with a virtual arm that performed a sequence of movements (see Figure 1). In order to study the proposed hypotheses, the system was used in 2 different configurations: action observation, and action execution with eye gaze. In the particular case of the action execution, the eye movement data was fed back to the system to control the movements of the virtual arm. For both conditions, eye movement data together with virtual arm movements were collected for later analysis.

2.3 Task

Participants were presented with a simple reach-and-grab and place-and-release task in the virtual environment. The environment was presented in a first person perspective, allowing the virtual arm to be consistent with the participant's point of view. The task consisted of grabbing a virtual ball (either with a left or right virtual arm), moving it to a target destination (which would make the ball disappear), then come back to the initial position and wait 3 seconds for the task to restart (see Figure 2). There were four pre-defined points for the ball's initial position, all equidistant to the target and symmetrical horizontally.

For the experimental trials, participants were presented with 2 different conditions, in the following order: (i) action observation – the participants were required to observe a pre-recorded

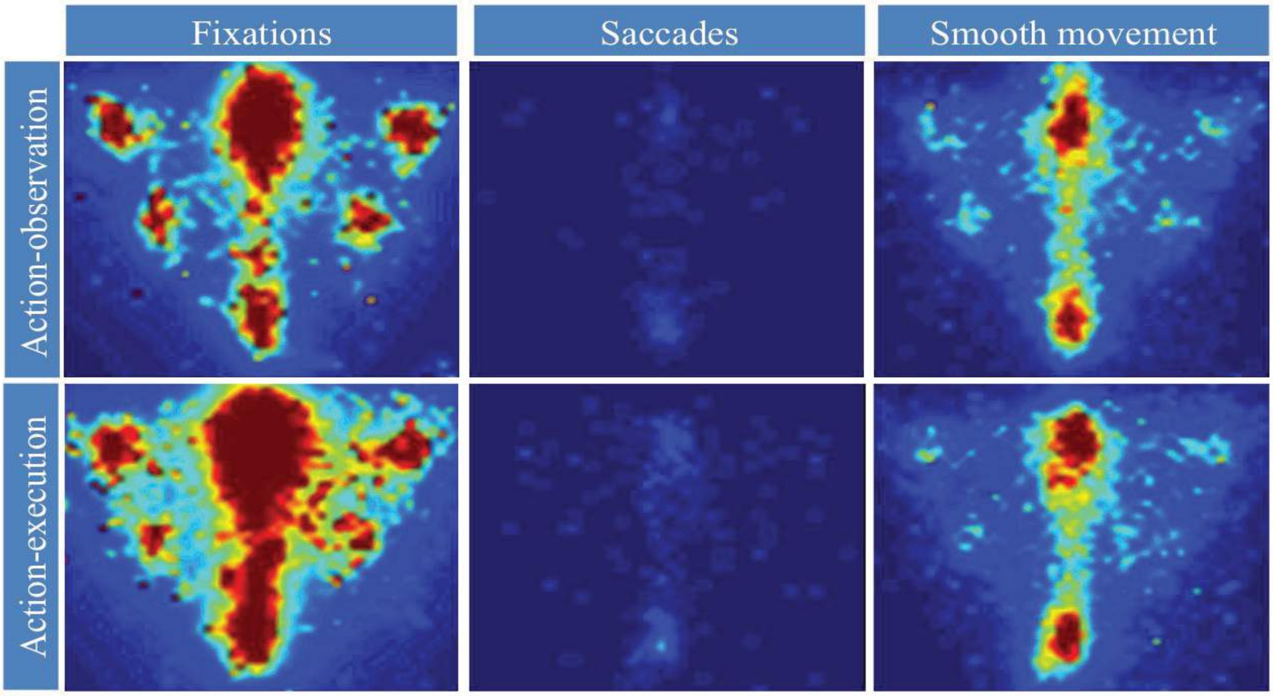

Figure 3. Density map for both action observation and action execution conditions according to the detected eye gaze patterns.

execution of the virtual arm grabbing the ball and taking it to the target destination; and (ii) action execution with eye gaze – the participants were required to actively grab the ball with the virtual arm using their eye gaze and take it to the target destination. For each condition, each participant had to perform (or observe) 40 repetitions of the task for each arm, with each repetition lasting around 5 s. The order of the initial position of the virtual ball was chosen randomly (out of the 4 predefined positions) for every repetition making sure that all initial positions were presented 10 times.

2.4 Data Analysis

All data analysis was performed with Matlab (MathWorks Inc., Natick, MA, USA). Eye tracking data was filtered with a Gaussian window of 1.6 seconds with $SD = 0.16$ s. Eye tracking data (X,Y) was then converted to screen coordinates. Data was removed from the segments where eye tracking data was missing and also during the resting periods. According to the velocity profile of the data, eye tracking behavior was classified into 1) fixations, 2) saccadic movements, and 3) smooth pursuit. For each behavior detected, the number of occurrences and their duration were assessed. In addition, the accumulated travelled distance was also computed.

Out of the 10 participants, 1 dataset of the action observation condition was corrupt and only 6 patients could complete the action execution task due the interference of stroke derived attentional or cognitive deficits.

The 2-sided Lilliefor test revealed that data was not normally distributed. A non-parametric test, matched pairs Wilkoxon test, was used to assess differences between paretic and non-paretic data on the same participants. To test against different conditions, where size groups differ in size (9 and 6), the non-parametric Mann-Whitney test was used to report differences.

3. RESULTS

A total of 9 stroke patients performed the action observation conditions whereas only 6 could complete the action execution condition.

A first analysis of the data classifying eye gaze patterns into fixations, saccadic movement, and smooth pursuit movements revealed very different spatial distributions (see Figure 3). In the context of the VR task presented here, fixations are mostly clustered around the location of targets (release place at the top-center and resting position at the bottom-center of the screen) or virtual objects (2 on the right and 2 on the left halves of the screen). Saccadic movements were detected mostly between the target position and the resting position. These two positions are always presented sequentially since every release at the target position is followed by a movement to the resting position to trigger the next sequence of actions. Because these two elements are at opposite ends of the screen they generate more saccadic movements. Smooth movements are detected mostly in the areas between virtual objects and their respective targets, which is congruent with the task at hand. Further, there is consistency when we compare eye gaze patterns between the 2 experimental conditions. There are no major differences between conditions and the distribution of eye gaze patterns triggered in response, finding congruent eye gaze patterns in action observation and action execution.

For the following analysis, we used 7 different metrics extracted from the eye tracking data: number of fixations, saccades and smooth pursuit segments, their duration and the overall accumulated eye gaze distance travelled (see table 2). An analysis of the number of fixations reveals clear differences between action observation (*Mdn*=1283) and action execution (*Mdn*=3241), $U=252$, $p<0.01$. Similarly, the number of saccades is significantly

Table 2. Median values of each eye gaze metric according to each condition and paretic or non-paretic arm.

	Action observation		Action execution	
	Paretic	**Non-P.**	**Paretic**	**Non-P.**
Fixation count	1295	1272	2955	3241
Fixation Duration	384 ms	376 ms	270 ms	298 ms
Saccades count	53	52	115	113
Saccades duration	271 ms	276 ms	286 ms	291 ms
Smooth count	361	403	535	497
Smooth duration	587 ms	567 ms	605 ms	589 ms
Distance	238 a.u.	283 a.u.	302 a.u.	311 a.u.

a.u. stands for arbitrary units.

lower in the case of action observation (*Mdn*=52) than for action execution (*Mdn*=113), *U*=276, p< 0.001. This finding is also consistent with the occurrence of smooth pursuit patterns, with *Mdn*=364 for action observation and *Mdn*=519 for action execution, *U*=238, p<0.05. Thus, there is a consistent increase of the number of fixations, saccades and smooth movements in execution as compared to observation. On the contrary, no differences could be found with the available data with respect to the duration of those events, except for a tendency to longer fixations in the action observation condition. No differences were found in distance travelled.

When we perform a within subject analysis to the different eye gaze patterns in response to the presentation of the paretic vs. non-paretic virtual arm, we find that patients do perform longer smooth pursuit when observing the paretic arm (*Mdn*=587 ms) than when observing the non-paretic arm (*Mdn*=567 ms), *T*=154, p<0.01. In average, smooth pursuit in the observation condition was 30 ms longer. However, no more differences were found in any other eye gaze metric.

4. CONCLUSIONS AND DISCUSSION

There is a growing body of research that supports the use of action observation as a valid rehabilitation tool post-stroke because of its shared neural mechanisms. In this study we approached action observation in a quantitative way by means of the combination of VR and eye tracking technology. However, the reduced sample size (9 + 6) and the potential measurement errors (however small) related to the eye tracker's accuracy may represent a limitation for the data collected.

Our data shows congruency in gaze metrics between action execution and action observation in stroke patients, as far as distribution and duration of gaze events (hypothesis a). However, significant differences in the total number of fixations, saccades and smooth pursuit segments suggest different underlying mechanisms for execution and observation. Observed increased number of events may reflect the differences between observation (open loop) and execution (closed loop) systems. Patients in the action observation condition performed longer smooth pursuit when observing movements of the virtual arm corresponding to their paretic arm. This difference may be explained by the recruitment of motor control areas of the brain affected by stroke (hypothesis b). However, no differences were found between paretic and non-paretic arm presentation in the action execution condition. Considering hypothesis c, this could indicate that eye-controlled action execution does not involve, at least to a large extent, the neural mechanisms of motor control affected by stroke.

The findings of this study suggest that eye tracking can be used to assess motor deficits derived from stroke. Future studies mapping the relation between brain areas that are affected by stroke and changes in gaze metrics could further extend the understanding between the shared neural mechanisms in action observation and action execution. Further, with the increasing appearance of low cost eye tracking devices, treatments aiming at exploiting the shared mechanisms between eye gaze control and action observation can become a cost effective continuous assessment and rehabilitation tool for at home use after hospital discharge.

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