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Validation of a Rehabilitation Platform for Visuomotor Perceptual and Cognitive Stimulation

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ABSTRACT

Stroke, or cerebrovascular accident, is a major global health condition and one of the leading causes of death and acquired disability worldwide. After a stroke, deficits in perceptual and cognitive functions may arise, of which impairments to visuomotor skills play a notable role. Because of that, an efficient therapeutic rehabilitation approach needs to include visual stimulation, and the ability to assess of how stroke patients deal with said stimuli. RehabVisual, presented in earlier works, is a digital platform that allows for an objective and standardized assessment of visuomotor skills. It allows also for the design of personalised clinical interventions for a given patient. In the current work, the platform's eye tracking abilities, which are an essential part of the rehabilitation scheme is thoroughly validated with healthy subjects. The process is performed through direct comparison between its accuracy and performance and that of a gold standard, state-of-the-art commercial device.

Keywords: Visuomotor rehabilitation, Digital platform, Eye tracking, validation

INTRODUCTION

Stroke, or cerebrovascular accident is a major global health condition, with a high risk of death. Around 15 million people suffer a stroke, yearly, of which one third will die and another third will be left permanently disabled (WHO EMRO, 2022). It can be estimated that one in four adults, over 25 years of age, will have a stroke in their lifetime (WSO, 2022). Even when surviving a stroke, neurological deficits may arise, with dramatic effects on the person's motor, sensory, cognitive and/or emotional functions. The ensuing disability levels range from mild effects to complete patient's dependence (Kasner, 2006). Rehabilitation plays a crucial role in mitigating those effects. Since

75% of all surviving patients will show significant degradation in visuomotor coordination, rehabilitation programs should always include stimulation of those competences (Colwell et al., 2021).

RehabVisual is a rehabilitation platform, built around a laptop, which is responsible for delivering visual stimulation and for collecting the subjects' gazing movements, both to evaluate their condition, as well as to develop more personalized interventions. It was developed, originally, for the assessment of visuomotor abilities in toddlers (Machado et al., 2018), and further evolved to support rehabilitation programs for stroke patients (Rodrigues et al., 2022). Although a preliminary evaluation of RehabVisual's usability has been done in the past, a systematic assessment of it has not been carried out in the context of stroke rehabilitation. More importantly, since the platform's performance depends considerably on the ability to accurately record and exploit the dynamics of the patient's direction of gaze, said accuracy needs to be ascertained.

The current study intends to give a proper answer to both validation requirements: accuracy assessment is performed through a comparison between simultaneously recorded eye tracking data from RehabVisual's webcam and a gold-standard device, the Tobii Pro Nano; as for the usability of the proposed rehabilitation apparatus, a System Usability Scale (SUS) test is answered by 14 rehabilitation professionals.

MATERIALS AND METHODS

Participants

The experiment was performed by 50 subjects, 26 of which female, with no known pathologies. 46% required eyesight correction through glasses or contact lenses, and 66% had right eye dominance. During the experiments, all subjects were asked to remove their glasses, yet guaranteed that stimulus was fully perceived. Ages ranged from 18 to 28, with mean value of 22 years for the female cohort, with a standard deviation of 2 years, whereas the male population had a mean value of 21, and a standard deviation of 1 year of age.

Experimental Setup

RehabVisual's overall experimental setup is shown in the centre of Fig. 1a. It comprises a chin-immobilizer, to ensure a fixed and correct relative position between the subject and the apparatus' ensemble screen-camera. One example of its use is given on the lower-left corner, in Fig. 1b.

The laptop's own screen and camera could have been used to deliver the visual stimulus, as well as to record the subject's evolving direction of gaze, respectively. Yet, to reduce visual clutter for the subject, while improving the quality of both the stimulation and the recording, a dedicated screen and webcam were employed instead. A very important added value to such configuration is that the webcam's data can be collected very close to where a Tobii Pro Nano is located. Hence, it is easier to compare the results proposed by the webcam's own gaze estimations and those of the state or the art's

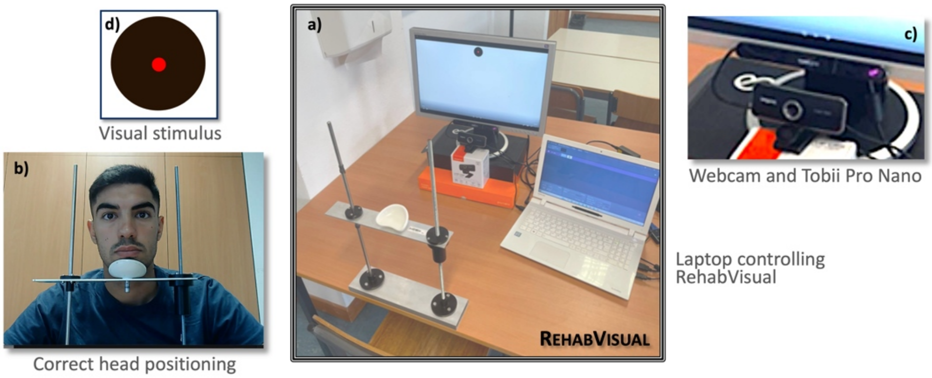

Figure 1: RehabVisual experimental setup, displayed in the centre, a). The lower-left frame, b), contains an example of use of the chin-immobilizer, whereas the upper-right one, c), zooms in on the webcam and Tobii eye tracker. On the upper-left corner, d), is displayed the visual stimulus employed throughout the experiments.

device. A zoomed portion of the recording setup, placed beneath the screen, is shown on the upper-right corner, in Fig. 1c. A final insert to the figure, on the upper-left corner, Fig. 1d, displays the stimulus employed throughout the experiment.

The screen and both eye trackers were raised to about 25 cm, over the table, to approximate eyesight level, and secure a comfortable viewing position for the subject. Also, the distance between the screen and the subject was kept close to 65 cm, for all participants in the experiment.

The display utilized was a Samsung SyncMaster 205BW (20”), whereas the webcam was a CREATIVE Live Cam Sync 1080p, with a diagonal field of view of 77°, with full HD (1920 × 1080 pixels) recordings, at 30 frames per second. The laptop used to drive the stimuli, as well as to record and process both the web cam and the Tobii data was a TOSHIBA SATELLITE L50-B.

Stimulus Conditions

Throughout the study, the stimulus circle moves, within the screen, as displayed in Fig. 2a. Each fixation point, from A to E, have a corresponding pair of pixel coordinates, which are shown in Fig. 2b, together with the evolution of the eight successive movements. Such stimulus setup was originally proposed in (Dias, 2020).

Prior to any visual movement, the stimulus was still for 3 s, in the beginning of each recording. The duration of every fixation, in each of the marked locations, was also of 1 s, for a total recording length of 34 s, as displayed in Fig. 2. To facilitate comparisons between the two trackers, data recorded via the webcam and Tobii were manually synchronized, prior to further analysis. The stimulus screen area corresponded to 1280x720 pixels.

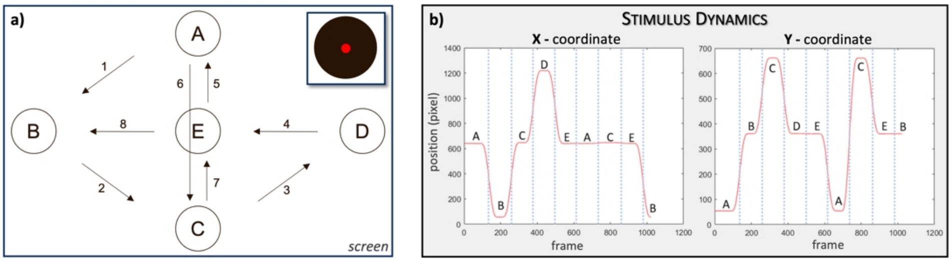

Figure 2: Stimulus on-screen evolution path, a) starting in A and ending in B. The pixel coordinates, for both the horizontal, X, and vertical, Y, directions are shown in b).

Measures of Agreement

Two different measures of agreement were drawn, from both eye tracking devices to confront RehabVisual's own approach to the gold-standard. The first, inspired by Tobii's quality assessment measures, consisted of the time spent in specific areas of interest. Within the calibration stimulus video, such areas were defined around the various fixation locations, A through E in Fig. 1. The areas themselves corresponded to regions, 30% larger than the black visual stimulus circle, centred on those fixation points. The other measure assessed consisted of the mean Euclidean distance between the estimated gazing locations and the actual stimulus positions, throughout the video.

Similarities and disparities between RehabVisual and Tobii eye trackers are evaluated via Bland-Altman plots (Bland and Altman, 1986). They are often used, in medical statistics, to compare a new measuring technique or method with a gold standard. It corresponds to a graph of the difference between those two measures, as a function of their average. In such a graph, a mean bias difference between the two measures can be drawn, as well as an agreement interval (AI), defined as the bias plus and minus 1.96 times the standard deviation of the difference between said measures (Myles and Cui, 2007). If both measures agree, and their distribution is normal, 95% of all observations should lie within that interval. Also, a bias closer to zero means that, in average, both measures return similar outcomes. To assess if a deviance from zero is significant, and a correction to such shift should be performed, one may define a 95 % confidence interval for the mean difference (IC95, in percentage) as $IC95 = b \pm t \times s^2/\sqrt{n}$, where n stands for the data sample size, t is the value of the t distribution with n *-1* degrees of freedom, b is the bias, and s the standard deviation of the difference between measurements. If the zero line, in a Bland-Altman plot lies within the confidence interval, one may say that there is no systematic shift between measurements.

An additional measure was calculated, as a summarising one, as a difference between the average distance between the true location of the stimulus, at any given time, and the estimated locations found by either method, for each eye.

RESULTS

Prior to analysing the Bland-Altmann plots of agreement between the proposed eye tracking device and Tobii's reference, one may have a quick visual inspection to the (x, y) tracking estimates of the direction of gaze, as displayed in Fig. 3, for both left and right eyes. The red line shows the true evolution of the visual stimulus coordinates, whereas the green and blue correspond to estimates by RehabVisual and Tobii, respectively.

The main perceptual information that one may draw from the figure is that both eye tracking devices follow, rather accurately, the X coordinates of the stimulus. Both left and right eye curves are noisier than the targeted output but identify correctly all transitions and fixations. Another interesting outcome is that the Y coordinate estimation seems a bit less accurate than the other coordinate, for both devices. Said difference may be due to variations in eyelid opening during vertical movements, which do not occur during horizontal eye displacements. Our goal is to ascertain that RehabVisual's performance is sufficiently close to that of the gold standard to be used in practise. Bland-Altman analyses do not guarantee accuracy of any of the studied methods. It only evaluates how close they are from each other. The validation sought relies completely on the quality of the target comparing approach. Hence, we chose a widely accepted eye tracking device.

Time in Areas of Interest

The Bland-Altman plot in Fig. 4 displays the overall agreement between estimated time spent in each area of interest, for both eye trackers. More

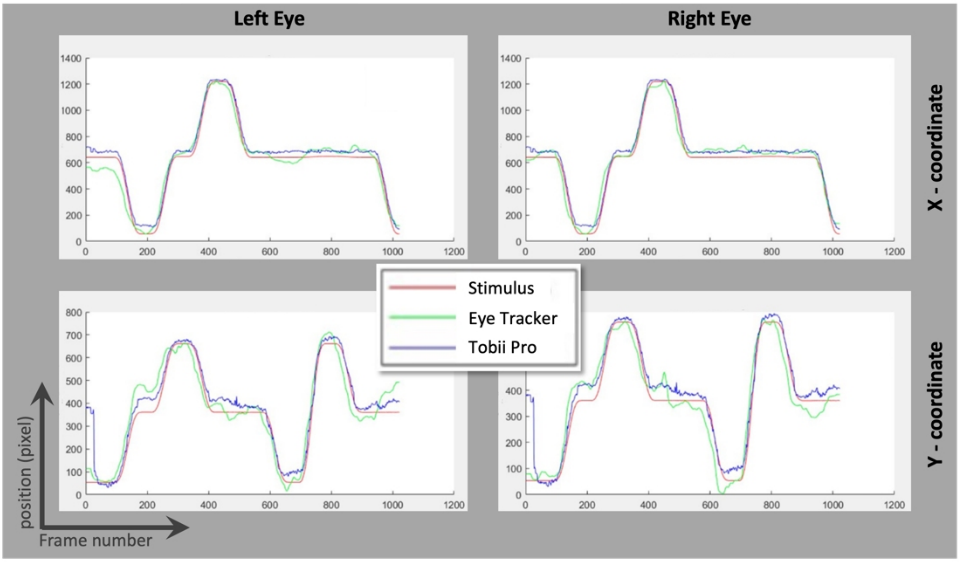

Figure 3: Eye tracking coordinates, as proposed by RehabVisual and Tobii Pro, shown as green and blue lines, respectively. True coordinates for the stimulus are shown in red. The left column corresponds to coordinates estimated for left eye movements, whereas the right column relates to the right visual tracking. X and Y coordinates are shown in the top and bottom frames of the figure, respectively.

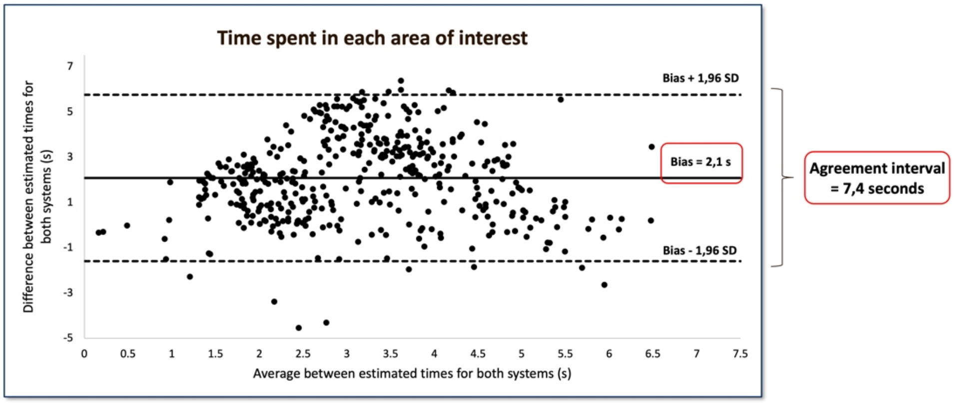

Figure 4: Bland-Altman plot for the overall agreement between time spent in all the pre-defined areas of interest, for both the RehabVisual and the Tobii Pro Nano eye trackers. The bias between both models and the 1.96 standard deviations are also marked.

detailed information, focusing also on individual fixation points, is presented in Tab. 1.

Table 2 introduces additional features, specific to each eye tracker, hence not visible from the Bland-Altman plot. They were considered of interest for a more thorough exploration of the relation between both devices. One such feature is the number of missed detections, which corresponds to areas for which the tracker returned a zero-fixation time.

Two significant outcomes can be drawn from both Fig. 4 and Tab. 1. One is that the interval required to hold 95% of all differences is rather large, with 7.4 s in duration. That value is greater than the intended fixation times set for each location point. One possible justification for that may be the definition of a region of interest, rather than a fixed location. The other result is the existence of a clear bias between both eye tracking methods. The bias, or mean difference is equal to 2.1 s, and the agreement intervals, for the complete set of areas of interest, as well as each one separately, does not contain the zero line, as clearly visible in Tab. 1. Since all values are greater than 0, one may conclude that RehabVisual's eye tracker tends to underestimate the values found by Tobii's.

Table 1. Detailed agreement results for the time spent in areas of interest. All stands for an average over all results obtained for each individual five areas.

Area	Bias (s)	Lower Lim AI (s)	Upper Lim AI (s)	− IC95% (s)	+ IC95% (s)
All	2.1	−1.6	5.8	1.7	2.4
A	2.7	−1.1	6.5	2.3	3.1
B	1.5	−0.6	3.6	1.3	1.7
C	1.7	−2.1	5.5	1.3	2.1
D	0.8	−1.0	2.5	0.6	0.9
E	3.2	−0.5	7.0	2.9	3.6

Table 2. Additional eye tracking characteristics, extracted from each individual device separately.

Area	Stimulus time (s)	Bias/ time (%)	Min time *Tobii* (s)	Max time *Tobii* (s)	Min time *RehabVis* (s)	Max time *RehabVis* (s)	# Missed detection *RehabVis*
All	23.0	9.1	7.6	23.3	0.3	21.2	75
A	6.5	41.5	2.5	6.8	0.1	6.2	11
B	3.2	46.8	1.8	4.1	0.1	4.4	19
C	5.2	32.7	0.2	5.9	0.1	7.3	4
D	2.4	33.3	0.1	3.2	0.2	2.8	35
E	5.9	54.2	0.6	8.2	0.1	6.4	6

A more thorough analysis of Tab. 1 tells us that the vertical line of stimulus evolution, corresponding to areas A, C and E, results in the poorest agreements between the two trackers, whereas the horizontal line, with B, D and, to some extent also C correspond to the highest agreements. Interestingly, B and D are also the areas that led to the highest rates of missed detections, as shown in Tab. 2. That may be explained by the fact that, around those areas, displacements are more vertical, which we have already established are less well estimated than horizontal ones, in part because of the longer trajectories of the latter.

One very important finding was that, although the chin support helped limit vertical head movement from the subject, it did not preclude head tilt, when following vertical stimulus displacements. This limitation may have been responsible for the discrepancy between eye tracking accuracies in in the horizontal and vertical directions.

Mean Euclidean Distances

The Euclidean distance between all estimated coordinates of the direction of eye gaze and the corresponding stimulus points was analysed also via a Bland-Altman plot, as displayed in Fig. 5, as well as some additional information that is gathered in Tab. 3. Note that data from both eyes is shown, leading to a total of 100 points, *i.e.*, twice the number of subjects in the study.

In line with the previous results, the proposed eye tracker somewhat overestimated this error measure. Also, the zero line is not comprised within the confidence interval, rendering the bias less consistent. Yet, if we keep in mind that the diameter of the stimulus, illustrated in Fig. 1, is of 88 pixels, a bias of 25 pixels represents only about 28 % of that size. Hence, the bias can be considered as rather small. The dimension of the agreement interval, 115 pixels, only about 1/3 greater than the stimulus dimension, in a 1280×720 screen, may be considered small.

With the results above one may defend the use of RehabVisual's apparatus to assess a patient's ability to follow visuomotor rehabilitation stimuli. Keeping in mind the maximum distance values for Tobii and RehabVisual, it

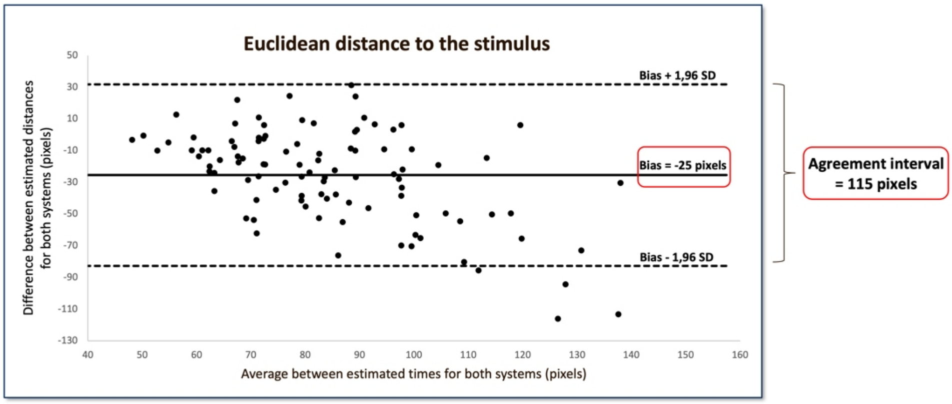

Figure 5: Bland-Altman plot for the overall agreement between Euclidean distances to the stimulus coordinates, between both eye trackers.

Table 3. Additional data for the comparison between mean Euclidean distances of the estimates.

	Bias (pixels)	Lower Lim AI (pixels)	Upper Lim AI (pixels)	- IC95% (pixels)	+ IC95% (pixels)
Euclidean Dist.	-25	-83	32	-31	-20

	Tobii		*RehabVisual*	
	Min (pixels)	Max (pixels)	Min (pixels)	Max (pixels)
Euclidean Dist.	40	123	50	194

seems safe to accept, as a reference, the ability to follow movements between objects distanced by, at least 200 pixels.

Direct Differences Between Eye Trackers

A final comparison between eye trackers was computed, resorting once more to the Euclidean distance, now applied directly to their estimates of the direction of gaze. When taking both eyes into account, the 100 pairs of estimates presented a mean distance of 108 pixels, with a standard deviation of 34 pixels. Once more, this value is very small when compared to the overall screen resolution of 1280×720 pixels.

If we separate left and right eye information, the former presented an average distance of 110 pixels, for a standard deviation of 38 pixels, whereas the latter showed 106 and 31 pixels, respectively. Hence, both eyes presented similar results, suggesting that the lighting conditions were sufficiently uniform to secure accurate and uniform treatment of each eye.

If one isolates X and Y coordinates instead, the horizontal distances range between 66 and 191 pixels, for a mean value of 73 pixels and a standard deviation of 31 pixels, whereas the vertical distances range from 27 to 143, for a mean of 65 and a standard deviation of 25 pixels. At first glance these results seem to contradict what we have observed earlier, since vertical displacements were more likely to be erroneous than horizontal ones. Yet, if we attend to the possible range of motion in X, 1280 pixels, and in Y, 720, the mean distances observed represent, in fact, about 5.7% of the horizontal scale, and 9% of the vertical one.

CONCLUSION

The main goal of this study was to assess the accuracy of, and possibly validate the eye tracking system integrated in RehabVisual, a digital rehabilitation platform, recently adapted to work with stroke patients. Said assessment addressed two main aspects of the eye tracker's functions: the ability to estimate correctly the position of visual attention onto a screen, with the concomitant ability to follow dynamically evolving visual stimuli; and the estimate of time spent in given areas of interest on a screen. Both studies were performed in comparison with a commercially available gold standard.

Although the estimates of time spent in areas of interest did not warrant a high degree of agreement between both eye tracking devices, that measure is does not have as high clinical value as the ability to identify, accurately, the direction of gaze. In that respect, RehabVisual's eye tracking system has shown to be within reasonable distance from the accepted gold standard.

The validated gaze tracking ability, together with fact that both stimulus delivery and eye tracking are performed in the same device guarantees synchrony between both streams of data. Recorded videos of those signals allow for the design of new and personalized clinical evaluation and intervention strategies, to be applied throughout the stroke rehabilitation program. Those may be used to complement physiotherapist's evaluation of patients and allow for the identification of possible changes in their visuomotor skills.

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