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Assessing stereo blindness and stereo acuity on digital displays

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ABSTRACT

Previous studies on stereoscopic acuity have shown that the percentage of stereo blind subjects is relevant. Moreover, stereoscopic visualization is becoming widely diffused in different fields, like, e.g., entertainment, surgery or VR training, where it is necessary an accurate assessment of stereoscopic abilities of the involved subjects. Therefore, there might be the need of performing a stereo blindness and stereo acuity test before each visualization session involving stereoscopic images. In this paper, we propose a method to assess stereo acuity and stereo blindness directly on the chosen device, under the same visualization condition and setup adopted for the tasks to perform, in order to have the same perceptual response. We present software-based tests suitable for a generic stereoscopic displays, and we compare their effectiveness performing a comparison with a standard physical, card-based, test commonly used in assessment of stereo acuity and stereo blindness. We provide to the reader all the details to perform autonomously the tests, of which images will be downloadable from web.

1. Introduction

In the recent years, the interest for stereoscopic visualization is growing rapidly in all the fields of research and application [1], thanks to the introduction of new hardware and software solutions.

In literature, we can find numerous sources covering the technical background of stereoscopic acquisition, visualization and printing [2,3]. Particular attention has been given to the issues related to perspective and geometric analysis [4], calibration and correction of stereoscopic acquisition systems [5,6], crosstalk in stereoscopic displays [7–9], and analysis and prevention of visual fatigue and discomfort [10–12].

Stereoscopy creates an illusion of depth by means of two images corresponding to different views of a scene. These images are sent to each of observers eye using specific hardware solutions. This simulates one of the major mechanism of human vision: most of the observers are able to process the differences between the two views (binocular disparity), elaborating the perception of depth (a process called stereopsis [13]). Observers with anomalies on this perceptual ability may have difficulties in combining correctly horizontal binocular disparities, and are called “stereoblind”.

Different studies have demonstrated that the percentage of stereoblind observers is relevant. A survey [14] has shown that among 150 students at M.I.T., about 4% has been unable to use the cue offered by disparity, and another 10% had great difficulty and has reported incorrectly the depth of a Julesz random pattern test [13]. In [15] it is reported that 14% of users (359 on a set of 2520 subjects) has been unable to see depth at the largest stereoscopic disparity tested, 450 seconds of arc, and have been classified as stereoblind.

Other studies, performed on large sets of people, have investigated the relationship between age and stereopsis [16–19], or have been focused on children, where stereopsis is developing [20,21]. These works have demonstrated that, even if stereoscopic vision of older subjects is comparable to that of younger observers in many aspects, age-related differences in stereopsis do exist, and they become most noticeable when the stereoscopic ability of older subjects is challenged by multiple simultaneous factors. These works has shown also that the threshold of stereo acuity decreases with age [18,20]. Other works have investigated the presence or absence of stereoscopic ability without reporting the individual’s level of depth discrimination [13]. In [22], the 97.3% of the considered population has been able to notice a depth difference at horizontal disparities of 2.3 minutes of arc

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or smaller, with at least the 80% able to detect depth differences at 30 seconds of arc.

Therefore, it is evident that testing stereo blindness and stereo acuity can be extremely important before a session involving stereoscopic visualization, in particular when stereoscopy is used in critical tasks, like, e.g. surgeries or VR training for risky tasks.

In most of the previous cited works, stereo blindness and stereo acuity have been assessed tested using well-known tests like the Randot, TNO, Titmus, Frisby, Lang II [23]. These tests, developed for clinical purposes by ophthalmologists, optometrists, and other eye care professionals and vision researchers, are based on printed cards with standardized symbols and patterns, and make use mainly of polarized glasses. Several works [19,24–27] studied and compared the validity and reliability of different stereo tests, coming to different conclusions about which test gives the most reliable results, or even debating on their actual effectiveness as screening tools. For example, in [19], all the subjects were able to achieve a stereo acuity of 3.3 minutes of arc with the Titmus test and 5.6 minutes of arc using the Frisby near stereotest. In a recent paper [27], the author states that random-dot stereograms are not the best possible choice for stereo blindness test, because their correct perception requires not only a correct stereopsis, but involves also other higher cognitive processes which initially require some time before a correct estimation. In other works, like in [28], improved versions of these kind of tests were proposed.

Starting from the experience in the design of the card-based tests, other scholars [29–32] have proposed computer based stereo blindness tests. Some examples of commercial products has been adopted widely, like the B-VAT II-SG system [33,34], a monitor-based system used for different visual acuity tests. Most of these products collected digital reproductions of the card-based tests, while others proposed improved or animation-based stimuli.

In general, those tests are implemented on dedicated systems, usually different from the devices used to accomplish the stereo task. In this way, the different conditions of stereoscopic visualization may lead to eventual different perceptual response. In fact, stereoscopic visualization depends on an accurate balance among different parameters, like, e.g. the initial disparity between the two stereoscopic views, the achievable parallax on screen due to resolution and dimension of the stereoscopic display, and the distance between the display and the viewer [2,3]. Even a subtle change in one of these parameters may affect the minimum representable depth or the minimum perceived depth.

For this reason, in this paper we propose methods to assess stereo acuity and blindness using the same visualization condition and setup adopted for the tasks to perform. Thus, it is possible to assess stereo abilities of the subject exactly with the stereo parameters used to accomplish the work. Therefore, there is the need for software-based stereo tests, installable and adaptable to the different possible visualization setups and devices. With respect to a physical test, a software-based test allows also a better control of parameters like luminance levels, which are much better controlled using a display, since the physical tests may suffer from varying and not optimal illumination condition, affecting the reliability of data, especially for small disparities.

In a preliminary work [35], we have proposed a first stereoscopic blindness test, inspired by similar stimuli adopted in physical tests. In this paper, we present the complete work, comparing the proposed software-based stereo blindness test (called *D_SB*) and stereo acuity test (called *D_SA*) with a physical test. In Section 2 we present a description of the physical test used as a reference for the proposed stereo assessment tests, and of the devices used during the experiments. In Sections 3 and 4 we describe the experimental procedures, the subjects involved and the obtained results from D_SB and D_SA software-based tests, compared to the corresponding stereo blindness and stereo acuity assessment methods present in the physical test adopted as reference. We conclude the paper with a final discussion in Section 5.

2. Apparatus

2.1. Physical stereo assessment test (Random Dot 2 Stereo Acuity Test)

We have considered the Random Dot 2 Stereo Acuity Test [36] for the comparison with the proposed software-based D_SB and D_SA stereo blindness and acuity tests. The Random Dot 2 Stereo Acuity Test uses polarized glasses. It consists of two different stereo blindness tests, together with one stereo acuity test. One of tests is aimed to children stereo assessment, and it has not been considered in this paper. The second stereo blindness test uses random-dot stereograms based on LEA Symbols® [37]. The test is composed by a 3 × 4 boxes grid, and in each row, three boxes contain a LEA Symbols® at a fixed disparity (500, 250 and 125 seconds of arc, respectively), and the fourth contains random dots only. Users must report for each box if they perceive an object at a different depth from the background, and they must identify the object shape.

The stereo acuity test is based on a graded circle test composed by 12 boxes, arranged in a 3 × 4 grid. In each box, three circles are depicted side by side, with only one circle placed at a not-null disparity. The set of disparities ranges from 400 to 12.5 seconds of arc. The circles are drawn using a black and thick border, and their background is a random dots pattern. Starting with the largest disparity in a descending scale, the subject is asked to identify the circle at each level that appears closer than the others. The last level for which the subject answers correctly is considered to be the level of stereoacuity.

The Random Dot 2 Stereo Acuity Test is shown in Fig. 1. The stereo blindness test is in the first page, while the stereo acuity test is in the first half of the second page.

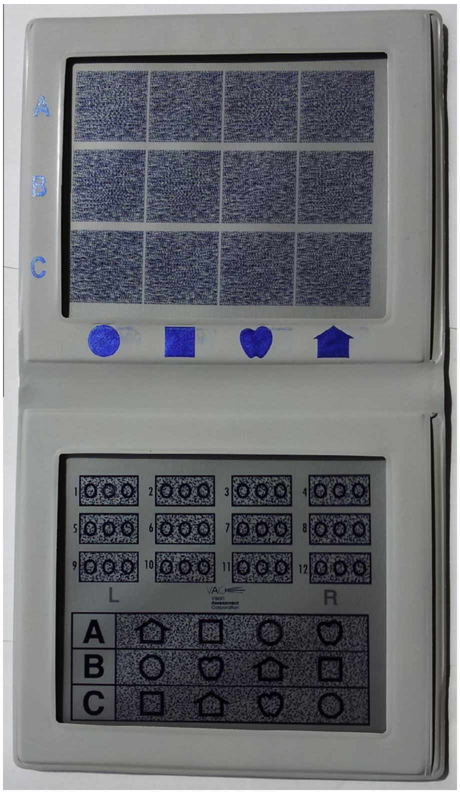

Fig. 1. Random Dot 2 Stereo Acuity Test.

2.2. Display characteristics

The display used in the experiments is a 21-in. BARCO prototype, 43 cm wide and 33 cm high, with a resolution of 1600×1200 pixels, equipped with passive stereoscopic visualization based on circular polarized filters. Horizontal pixel pitch is 0.27 mm. This value is equal or similar to the majority of standard desktop monitors.

2.3. Relation between on-screen and on-retina disparity

We introduce the relation between parallax on the screen and the disparity on the retina, as in Fig. 2, where d is the disparity between the two images, expressed as follows:

$$d = \frac{sw}{hr} \cdot sp \tag{1}$$

In Eq. 1, sw is the screen width in cm, hr is the spatial horizontal resolution of the screen, and sp is the screen parallax in pixel. Knowing the distance D between the screen and the observer O, we can express d as an angle α in radiant with the following formula:

$$\alpha = 2 \cdot atan\left(\frac{\frac{d}{2}}{D}\right) = 2 \cdot atan\left(\frac{d}{2D}\right) \tag{2}$$

3. Stereo blindness test

The test we have proposed in [35] used solid gray filled squares on a random dots pattern (we will provide further details in Section 4).

The cortical nature of stereo visual processing is quite established, with different functional descriptions according to the kind of visual task involved, like object recognition, or visual spatial perception and visuomotor control [38–43]. The approach followed in [35] is based on object recognition, while in many physical tests stereo blindness assessment is based on stereograms, where there are no edges to drive object recognition. Even if some critics have been proposed on the use of stereograms [27] for stereo blindness assessment, we have decided to consider also a set of stimuli with no edges. To this aim, in the proposed D_SB test we have replicated the stereograms included in the Random Dot 2 Stereo Acuity Test, and we arranged it in a sequence following the same scheme of the physical test.

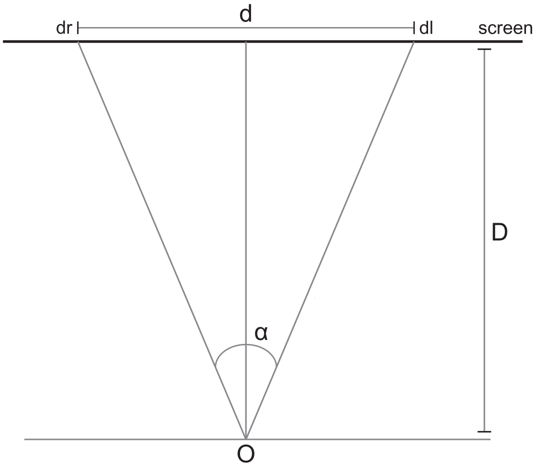

Fig. 2. Scheme of parallax d as an angle α.

3.1. Subjects

19 subjects participated to the experiment. The observers were 12 males and 7 females, between 23 and 68 years old (average age 38.26 years). All of them have normal vision or corrected-to-normal vision.

3.2. Procedure

We have performed the tests in two following sessions, in the same sound-attenuated room.

3.2.1. Physical test (Random Dot 2 Stereo Acuity Test)

Before the beginning of the test, the subjects have been informed about the procedure, and they were shown the 4 LEA Symbols® present in the test.

They have been given the booklet (folded so to have only the first page with the stereo blindness test visible), and instructed to keep it at around 40 cm to their eyes. They have been placed under an artificial light, and they have been allowed, if needed, to tilt the booklet in the best position to avoid reflections. The room was fully lighted, with standard consumer fluorescent lamps. We measured a luminance of around 70 cd/m^2 from a white reference paper.

Starting from the first box, without time constraints, they were asked to identify the object, or to report the box as empty.

3.2.2. Software-based test (D_SB)

Using the formulas presented in Section 2.3, we created a set of digital stereograms in order to match the same disparities on retina with the monitor described in Section 2.2, with the user at the distance of 1 m. Table 1 shows the disparities in pixels of the digital stereograms.

The sequence of digital stereograms have been shown to the subjects, and they have been asked to perform the same task as in the Random Dot 2 Stereo Acuity Test (i.e., identification of the objects or report of absence of disparity). Between each image a black picture was shown for 2 s in order to avoid bias due to visual persistence.

Each image of the test sequence has been exposed without time constraints, and the observers have been allowed to move their eyes, so they could freely change their fixation point during estimation. They have been asked to not lean towards the display so to not change viewing distance. They have not been given any feedback about the correctness of their estimation during the test. The room was darkened by switching off the lights.

3.3. Results

During the D_SB software-based test, 18 subjects (94.74%) have given correct responses. During the sessions with the Random Dot 2 Stereo Acuity Test, 7 subjects (36.84%) have not answered correctly to some of the cases in the second and third row (250 and 125 seconds of arc). Among these, 6 subjects have been able to perceive the presence of disparity, but they have identified a different (even if very similar) shape, while one subject has reported all the boxes in the third row as empty. These results seem to be in line with the critics presented in [27], where random dots stereograms

Table 1
The disparities considered in the proposed D_SB stereo blindness test (first row), with the correspondent pixel parallax in the stereoscopic pair (second row). The distance of the subjects from the screen is 1 m.

Disparity (arc sec)	500	250	125
Disparity (pixel)	9	4	2

were criticized for the use of shape identification. Moreover, most of these subjects have reported that they considered not sufficient the illumination present in the room for those cases. However, we have kept the same experimental conditions in the stereo acuity test of the Random Dot 2 Stereo Acuity Test (presented in Section 4.2.2), and, in this case, the same subjects have not reported problems with the level of illumination, and they have made a correct estimation at the same disparity. A possible explanation for this behavior, as suggested by one of the reviewers, could be related to micro-strabismus or monocular suppression. The subjects have not been tested for these conditions, and further investigations will be considered in additional experimental sessions.

One subject has reported that she has received a surgical correction of strabismus. The subject has not been able to answer during the experimental sessions, not perceiving, as expected, any presence of disparity.

4. Stereo acuity test

In order to develop the D_SA software-based stereo acuity assessment test, and to perform a comparison with the stereo acuity test of the Random Dot 2 Stereo Acuity Test, we have decided to adapt and improve the experimental setup we have proposed in [35].

The design of the software-based test has derived from the analysis of the available physical tests. The test patterns have been adapted to digital in order to obtain the following characteristics.

Shapes have been kept simple to recognize, and easy to distinguish from the background. The final choice for the foreground stimuli has been a set of three squares, placed side-by-side, with the same color (digit 128 middle gray). We have chosen squares in order to avoid anti-aliasing problems with curved lines. After some pre-tests with different scale of grays, the subjects have reported the same results but with a more comfortable test experience using a middle gray [35].

The choice of the background is a critical element, because the ideal neutral background does not exist. In stereo blindness or acuity assessment, the background must be chosen in order to achieve a clear separation in perceived depth between the background and the foreground stimuli. A uniform color (i.e. white, or black) as background is not convenient since it changes the appearance of the scene. Alternatively, a fixed pattern-based background may introduce monocular depth cues.

Thus, the final choice for the background has been a white noise random-dots pattern, as used in other works [44,45]. In [35], we have tested two different version of random-dots backgrounds, based on different values of spatial frequency. According to the results, we have chosen the higher spatial frequency background. In Fig. 3 we show a monoscopic preview of the test scene.

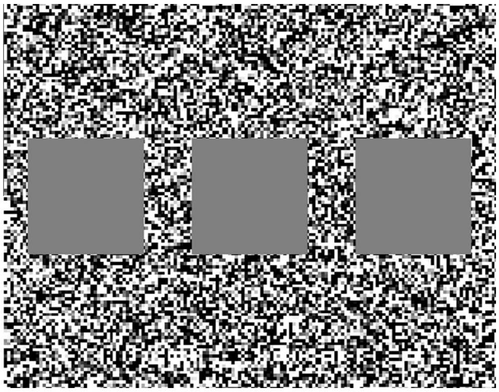

Fig. 3. A monoscopic preview of the stereoscopic images used in the D_SA software-based stereo acuity test.

The D_SA test consists in a sequence of 10 stereoscopic images. In each image, one of the three squares is randomly presented with varying disparity values, while the others are presented at zero parallax. In each image, the subject must report which square is perceived in front of the others.

The considered disparities match a subset of those present in the Random Dot 2 Stereo Acuity Test, and are listed in Table 2.

4.1. Subjects

42 subjects have participated to the experiment. The observers were 28 males and 14 females, between 21 and 68 years old (average age 30.28). All of them have normal or corrected-to-normal vision. 16 subjects have participated also to the stereo blindness test presented in Section 3.

4.2. Procedure

We have performed the physical and the software-based tests in two following sessions in the same room of the stereo blindness test (see Section 3).

4.2.1. Physical test (Random Dot 2 Stereo Acuity Test)

Before the beginning of the test, the subjects have been informed about the procedure. They have been given the booklet (folded so to have only the second page with the stereo acuity test visible), and instructed to keep it at around 40 cm to their eyes. The position and illumination conditions have been the same as in the stereo blindness test, described in Section 3. Starting from the first box, without time constraints, they have been asked to identify in each box the circle perceived in front of the others. Even if in our D_SA software-based test we have considered only a subset of the disparities present in the Random Dot 2 Stereo Acuity Test, in this session we have performed the full test.

4.2.2. Software-based test (D_SA)

To match the disparities on the retina in our D_SA software-based stereo acuity test with those of the Random Dot 2 Stereo Acuity Test, we have calculated for each case, using the formulas of Section 2.3, the correct disparity on screen (i.e., the amount of parallax in pixel between the two views) and the relative distance from the screen. Table 2 shows the values of these parameters for each considered disparity for the used display.

The physical dimension of the pixel limits the minimum amount of disparity representable on a screen, and therefore to assess fine levels of stereo acuity it is needed to place the subject, in some cases, at long distances from the screen. This may not be possible in some stereoscopic visualization setups, and therefore it can be a critical parameter to consider during the design stage of a new stereoscopic visualization environment, or during the preparation of stereoscopic material to visualize in a particular setup. Moreover, a relative decrement of average luminance occurs due to the change of viewing distance. However, high resolution stereoscopic displays will be more and more available, leading to a decrease of equivalent viewing distances.

The procedure of the proposed D_SA stereo acuity test has been very close to those described in Section 3 for the D_SB stereo blindness assessment: the sequence of test images has been shown in the darkened room, with a 2-s black interval between each image, the subjects had no time constraints, and they have been allowed to move eyes and head freely, while keeping the distance between their head and the screen constant. Subjects have been instructed to not guess, reporting absence of disparity according to their perception. They were not given any feedback about the correctness of

Table 2
The disparities considered in the proposed D_SA software-based stereo acuity test (first row), with the correspondent pixel parallax in the stereoscopic pair (second row) and distance between the subjects and the display (third row).

Disp. (arc sec)	160	100	63	50	40	32	26	20	16	12.5
Disp. (pixel)	2	2	2	2	2	1	1	1	1	1
Dist. (cm)	69	110	174	215	277	174	215	277	346	443

their estimations. Fig. 4 show a subject during an experimental session.

4.3. Results

In Fig. 5 we show, for each disparity and for both tests, the percentage of subjects which have correctly answered. In the D_SA software-based test, we presented the full sequence of 10 disparities as well as in the Random Dot 2 Stereo Acuity Test, without considering in this analysis any correct answer given after an incorrect one.

The results seem to confirm the substantial equivalence of the two tests, down to the disparity of 26 seconds of arc.

It is important to notice how this disparity is below the threshold of normal acuity, under which it is registered a decrement of performance. This threshold has been measured in 60 seconds of arc (corresponding to the detail size on a 20/20 Snellen chart) [46,47], while in other works [48,49] a lower value (30 seconds of arc, corresponding to the detail size on a 20/10 Snellen chart) has been reported. In this paper, we consider the values between 32 and 63 seconds of arc (the closer values in the Random Dot 2 Stereo Acuity Test) as the upper and lower bounds for the average stereo acuity threshold, and, for the sake of completeness, we report also three lower values of disparity tested.

From these data, it is difficult to say which of the two tests is more suitable for values under the normal resolution limit. In fact, hyperacuity is proven to be dependent on the spatial configuration of the pattern used to test [47,50], and on other parameters, like, e.g. luminance. Tests for hyperacuity are generally performed for special purposes that are out of the scope of both the tests considered in this work.

For a more detailed analysis, we present in Fig. 6 the individual stereo acuity measured in each subject in both the tests.

From this graph, 11 subjects (26.19%; subjects 1, 24, 25, 27, 31, 34, 36, 37, 38, 39 and 41) present a stereo acuity coarser than 32 seconds of arc in both tests. Among them, 7 subjects have a stereo acuity between 63 and 32 seconds of arc at least in one of the two tests.

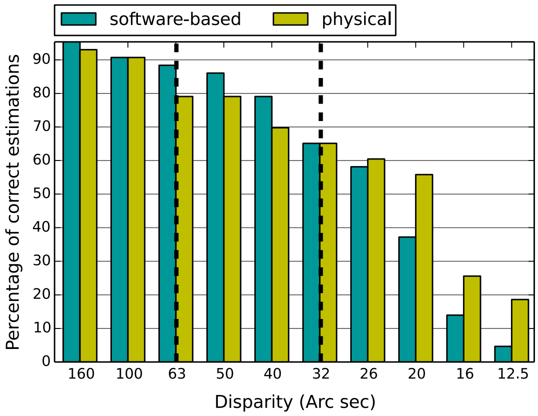

Fig. 5. Percentage of correct evaluations for each disparity. The dashed lines mark the range of disparities in which falls the stereo acuity threshold.

3 subjects (7.14%; subjects 27, 31 and 39) may be classified as possible stereoblind. Subjects 27 and 31 have given only one answer in the D_SA software-based test, and zero and two correct answers, respectively, in the Random Dot 2 Stereo Acuity Test. They have reported severe eye fatigue after the D_SA test, and both have stated to have never had a stereoscopic assessment test before. Both the subjects have not participated to the stereo blindness test presented in Section 3. Subject 39 has given two answers in both the D_SA software-based test and the Random Dot 2 Stereo Acuity Test. The subject has not reported eye fatigue after the tests. However, the subject has reported to have been diagnosed with nystagmus, a condition whose effects on binocular vision have been investigated in different works [49]. Interestingly, in the stereo blindness test presented in Section 3, the subject has given correct responses in all the cases during the D_SB software-based test, while in three cases (one at 250 and two at 125 seconds of arc) of the Random Dot 2 Stereo Acuity Test she has correctly detected the presence of disparity, but has reported a slightly different shape. This seems to suggest that the subject is able to perceive correctly large disparities, but not depth differences of smaller details.

Subject 38 is the known stereoblind subject with corrected strabismus who has participated also to the stereo blindness test (see subSection 3.3), and has reported to not perceive any disparity in both the tests.

Other 4 subjects (12.12%; subjects 2, 4, 21 and 33) present a different behavior among the two tests, with a stereo acuity coarser than 32 seconds of arc in only one of the tests (subjects 2 and 4 in the Random Dot 2 Stereo Acuity Test, subjects 2 and 4 in the D_SA software-based test). However, for all these subjects the coarser value of tested stereo acuity falls in the range between 63 and 32 seconds of arc, and therefore we can consider them to have a normal stereo acuity.

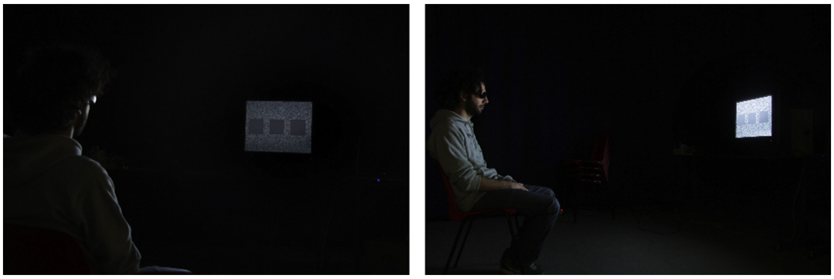

Fig. 4. A subject during an experimental session.

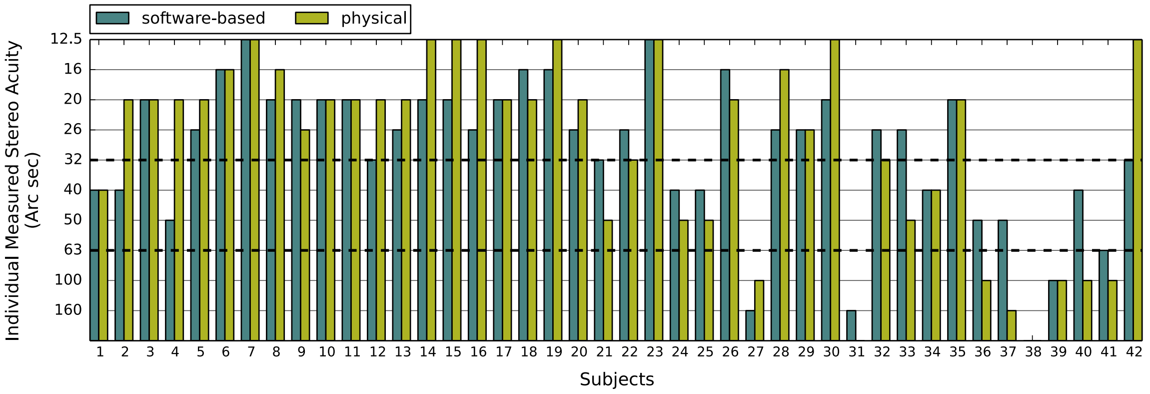

Fig. 6. Individual stereo acuity measured for each subject in both the tests. The dashed lines mark the range of disparities in which falls the stereo acuity threshold.

5. Conclusions

In this paper we have presented a stereo blindness (called D_SB) and a stereo acuity (called D_SA) test to be performed on a stereo display. The idea is to perform an assessment of stereo vision of the subject directly on the device she/he will use for the stereoscopic working task. To validate the proposed tests, we have presented a comparison with a standard card-based test (Random Dot 2 Stereo Acuity Test) commonly used in clinical assessment of stereo acuity. We have replicated in D_SB and in D_SA the same disparities present in the Random Dot 2 Stereo Acuity Test, and we have performed experimental sessions with several users. From an analysis of the results, the software-based stereo assessment tests can be considered equivalent to a physical test.

All the images necessary to perform the proposed D_SA stereo acuity test (Section 4) are downloadable from the web page [51]. It is possible to select from a set of standard display resolutions, and to download the correspondent set of test images. Moreover, it is possible to calculate, on the basis of the formulas described in Section 2.3, the correct viewing distance, given the horizontal resolution and the width of the stereoscopic display.

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