DOI 10.34658/9788366741102.1

Objects' colors impact on scene image perception in immersive virtual environments

Jarosław Andrzejczak[0000−0002−4124−0110]**, Marcin Lenarczyk**

Lodz University of Technology
Institute of Information Technology
Wólczańska 215, 90-924 Łódź, Poland
jaroslaw.andrzejczak@p.lodz.pl

Abstract. *Objects' color perception, including these in virtual space, plays significant role in looking for information, rating content and navigating. Prepared research environment consist of five individual experiments focused on analysis of color (especially its contrast) impact on objects perception in virtual space. Both quantitative data from virtual environment and qualitative data from questionnaires have been acquired. Results from one task showed, that there is a correlation between high color contrast and memorization efficiency. At the same time, in accordance with verified results we can't be certain, that colors having high contrast with surroundings are selected first, better noticed and chosen faster.*
Keywords: *Color contrast, Color perception, Objects perception, Virtual Reality, VR space perception*

1. Introduction

Objects' color perception, including these in virtual space, plays a significant role in looking for information, rating content and navigating. Color is inseparably connected with contrast. This article presents research verifying color contrast influence on objects perception in virtual space. Research conducted in few last years (e.g. [1, 2]) mainly refers to two-dimensional environment such as websites and single images. They focused on color contrast perception, its analysis and influence on user behaviour. This paper presents research conducted in a three-dimensional virtual environment. This allowed us to analyze uncharted aspects of color contrast, such as influence on remembering and order of choosing objects. Introduced experiments may be encouragement for future research in this field.

The contributions to research concerning objects' colors impact on scene image perception in immersive virtual environments presented in this article are:

- Confirmation of the correlation between high color contrast and memorization efficiency in VR.
- Tests verifying the impact of objects' color contrast on its perception in virtual space in case of memorization efficiency, search performance and distinguishing objects.
- Analysis of user's eyes motion (saccades and fixations as well as areas of interest - AOI) during the searching, grouping and memorizing tasks in VR.

We start with an analysis of related work through several past years has been done to show the present state of the art. Secondly research method have been described including formula for calculation of color contrast, prepared set of colors, method of data analysis, research stand and virtual environment with five experiments. In the next step, we present the way research have been conducted, discussing one task at the time. Afterwards we show the test results including both quantitative and qualitative data along with their analysis and conclusion. At the end, we summarize the whole research process.

2. Related work

Several papers [3, 1, 4, 5] base on, known from XIX century, simultaneous color contrast [6]. Roberts [3] questions three issues propositions about the colors (Incompatibility, Realism and Objectivism) by referring to statement linked with relationship between color of objects and color of objects surrounding them. Soranzo [1] presents few interesting cases, where objects' color and luminance perception is related to surrounding areas. Ratnasingam and Anderson in paper [5] show a method for assessing simultaneous contrast which improves issues of methodology connected with nulling and matching experiments as long as reduces contribution of temporal adaptation.

Lewandowska et al. [2] focus on better understanding of contrast perception in different cognitive styles by using psychometric questionnaire known as FRIS. Research procedure assumes modifying images from Fotolia collection in terms of contrast (low, reference, high). Afterwards, same image is being presented in two variants with different contrast. User have to point, which image has better quality. In conclusion, they say, that "subjects' preference to images with different contrast level are a function not only of image content but also human cognitive style" [2].

Pelet and Taieb in their research [7] verify influence of color contrast on behavioural intentions of subjects. Experiment includes preparing two versions of a mobile website specializing in selling CD's with music - one with positive contrast (yellow text on green background) and another with negative contrast (green text on yellow background). The website with positive contrast has been visited by 160 subjects. This with negative contrast - by 152. After task including choice of at least two CD's, questionnaire have been given to subjects. This questionnaire focused on website design, perceived dominance, mood, trust for website, intention to revisit and intention to recommend. In conclusion of this article, color contrast has significant impact on behaviour and decisions of users.

Souza et al. [8] make a review of researches using various mosaic images for color and luminance evaluation. They notice, that "perception of luminance and color contrast between objects and their environment is fundamental for behavioral tasks carried out by primates (including humans)". What's more, they point, that object is visible when it has good contrast with surroundings. Authors claim, that contrast should be at least one of five attributes of visual scene (brightness, texture, movement, color and binocular disparity).

Nieves et al. [9] present correlation between color and spectral reflectance of surfaces and spectral power distribution of light falling on them.

Ma and Zhang in their paper [10] present a method for searching attention areas in images based on generic contrast. It's worth to notice about the assumption, that areas which attract attention contain a lot of data. In calculations, they transform color space from RGB to LUV as the latter closer represents human color perception.

Tregillus and Webster [11] explore adaptation distribution of chromatic contrast.To achieve it, they conducted research in which color squares have been shown in specified time intervals. Experiment sessions took 5 consecutive days. Results show sudden changes in perceived contrast with chromatic contrast adaptation.

Hryniewska and Salvatore in [12] conducted research focused on verifying the role of luminance, color and contrast in perceiving and remembering objects. The experiment included 360-degree panoramas displayed in virtual reality space. Results show, that "contrast and luminance played a much larger role during looking for objects, than during memorization". One of the above authors also provided guidelines for testing VR applications [13].

Analysis of papers clearly shows that research connected with color contrast have been conducted in two-dimensional environment, such as websites, single images, as long as in real life environment [9]. Also, panoramas in virtual reality space have been presented. None of found papers connect color contrast perception with three-dimensional, virtual environment, including additional factors like lighting and user's movement, minimizing at the same time immutability of experiment conditions.

3. Experiment

The aim of the study was to analyze the 3D objects' color contrast impact covering most of the typical users' tasks in VR, namely:

- selecting,
- following moving object,
- searching,
- grouping objects,
- memorizing.

Therefore, the study session was divided into five individual experiments - each one focused on one particular behaviour in VR.

The hypotheses for this experiment are as follows:

- **Selecting**: *H0 - Objects with higher contrast are selected faster. H1 - Users' attention on objects with the same contrast it does not spread evenly.*
  In order to verify the H0 hypothesis, an analysis of the contrast of successively selected objects was performed (sorted according to the mean selection times).

- **Following moving object**: *H0 - Objects with higher contrast are better perceived.*
  The verification of the H0 hypothesis consisted in analyzing the eye-tracking data containing the generated summary heat maps for each stage of the task.

- **Searching**: *H0 - The time needed to find objects with higher color contrast is less than objects with lower color contrast.*
  In order to verify the H0 hypothesis, the times of finding individual objects were measured from the beginning of a given stage of the experiment and from the moment of finding the previous object. Then the average pointing times for a given object were verified taking into account the color contrast.

- **Grouping objects**: *H0 - Objects with similar color contrast are perceived similarly. H1 - Objects with more color contrast are selected first.*
  In order to verify the H0 hypothesis, the distribution of objects in individual groups was examined, taking into account their color contrast between the halves of each of the objects (with a distinction between high and low). In order to verify the H1 hypothesis, the order of assigning successive objects was analyzed, taking into account the color contrast between the halves of each of them.

- **Memorizing**: *H0 - Objects with higher color contrast are remembered better. H1 - Colors with higher contrast are selected first.*
  In order to verify the H0 hypothesis, the number of correct answers and their ratio to the number of errors made while remembering the object were analyzed. In order to verify the H1 hypothesis, the order of assigning individual colors was analyzed.

The experiment was split into three individual stages. First, the pilot study was conducted. Next day, second stage took place - four tasks were conducted. The last stage started four days after the previous one and included one task which was repeated twice. In all experiments (excluding pilot study) fifteen subjects participated. Research group was differentiated both in terms of age and eyesight defects.

4. Research method

4.1. Calculating color contrast

Conducted research include method for calculating color contrast presented by W3 consortium [14]. According to guidelines, "Two colors provide good color visibility if the brightness difference and the color difference between the two colors are greater than a set range". Considering the characteristics of research, we used a formula for calculating color contrast (1) [15].

$$\begin{aligned} C_d = {} & (max(R_1, R_2) - min(R_1, R_2)) + \\ & (max(G_1, G_2) - min(G_1, G_2)) + \\ & (max(B_1, B_2) - min(B_1, B_2)) \end{aligned} \tag{1}$$

where R, G, B are components in RGB space, with range 0-255.
Range of result values in formula (1) is 0-765. According to consortium guidelines [15] we took 500 as a threshold for determining high (>= 500) and low (< 500) contrast.

4.2. Eye-tracking data analysis

Data collected from eye-tracker have been processed using Ogama [16]. However, this software doesn't explicitly allow creating summary heat maps from specific parts of many recordings. In order to create heat maps based on part of recording, data have been exported from Ogama to csv file format. Next, we generated heat maps using examples [17] of D3.js library [18].

4.3. Set of colors

Set of colors used in experiments have been elaborated by using data from two sources: doctoral thesis by PhD Radosław Bednarski [19] and W3 consortium website (chapter 4.2 Recognized color keyword names [20]). In the first case, colors have been selected arbitrarily from the set which fulfilled criteria given in formula (1). In the second case, all colors included in the website's set have been retrieved. Basing on the created set (including examples of combinations of colors), collection of colors for individual experiments has been developed.

4.4. Additional method for calculating color contrast

In our experiments besides calculating base contrast we used method for calculating color contrast including lighting on virtual scene. To achieve that, the following algorithm (which iterates through the whole set of objects in the current stage of experiment) has been implemented:

- It sets the camera's position in the center of current object (ball).
- It sets the color of object to white (RGB(255, 255, 255)) and surrounding objects color to black (RGB(0, 0, 0)).
- It takes part of the screen (later in article named as mask) with dimensions specified in formula (2) to include all objects located in the nearest environment.
- It sets objects' colors to initial values.
- It takes part of the screen with specified dimensions again.
- By using mask and colored part of screen, it calculates color contrast.
- It saves data in JSON format.

$$D = \left(\frac{width}{6}, \frac{height}{4}\right) \tag{2}$$

Where: D - dimensions of part of screen, *width* and *height* - dimensions of view area.

4.5. Calculating color contrast based on mean colors of object and its surroundings.

In its base form, the algorithm splits pixels of colored part of the screen into two separate lists: pixels belonging to verified object and these belonging to surroundings. To achieve that, we took into account the following criteria:

If $R < 0,02$ *and* $G < 0,02$ *and* $B < 0,02$ *that pixel belongs to surroundings, otherwise it belongs to verified object (ball).*

It's worth to notice, that here we operate in 0,0 - 1,0 RGB range. Afterwards, we calculate average color for the object and its surroundings using arithmetic mean. In the next step, we pass mean colors to methods calculating color contrast. In advanced version, the algorithm works in the following way:

- It iterates through colored part of screen with 30 pixels step (both horizontally and vertically).
- Basing on mask, it checks if pixels belongs to object (ball) or its surroundings.
- It takes all pixels belonging to surroundings located in 30x30 pixels square.
- It calculates mean color of these pixels using arithmetic mean.
- It calculates mean color of object, like in base version, using arithmetic mean.
- After calculating mean color, for each 30x30 pixels area, it computes color contrast between average object's color and average color of this area.
- Finally, it calculates average color contrast (using arithmetic mean) considering all color contrasts computed in previous step.

4.6. Hardware and virtual environment software

Research have been conducted using ASUS R510L laptop with 1366x768 pixels screen. Interactions between device and user were provided by the laptop's keyboard, wireless mouse (in case of pilot study) and by wired mouse (in case of actual experiments). For eye-tracking purposes, we used The Eye Tribe hardware [21]. We also had an opportunity to use Tobii EyeX [22]. Available software was difficult to use (allowing for eye-tracking only with prepared videos) and gave very weak results (showed gaze areas didn't coincide with actual user's gaze points). Despite this, we rejected this option. The environment prepared for research also included a second monitor used for verifying the experiment process by the study supervisor. It was placed in such a way, that it wasn't distracting to subjects.Virtual research environment has been implemented using Unity, ver. 2018.2.15f1 (64-bit) [23] and Visual Studio 2017 [24]. During development process, C# programming language has been used. We prepared five three-dimensional scenes - one for each experiment. Scenes have solid, white background (RGB(255, 255, 255)), for reducing environment influence on perceiving objects by subject.

4.7. Questionnaires

For the purposes of research, four questionnaires have been created based on standardized questionnaires and UI/UX testing guidelines [25, 26]. Three of them were directly connected with specific task and included questions about experiment process and subjective feeling of subject. The fourth one included questions characterizing the subject in terms of age, sex, eyesight defects, experience in computer games and susceptibility to motion sickness. Each of the questionnaires had only few questions and statements to fulfill, because we wanted to reduce fatigue during experiments. All questionnaires presented after experiments had answers presented in 5-degree Likert scale.

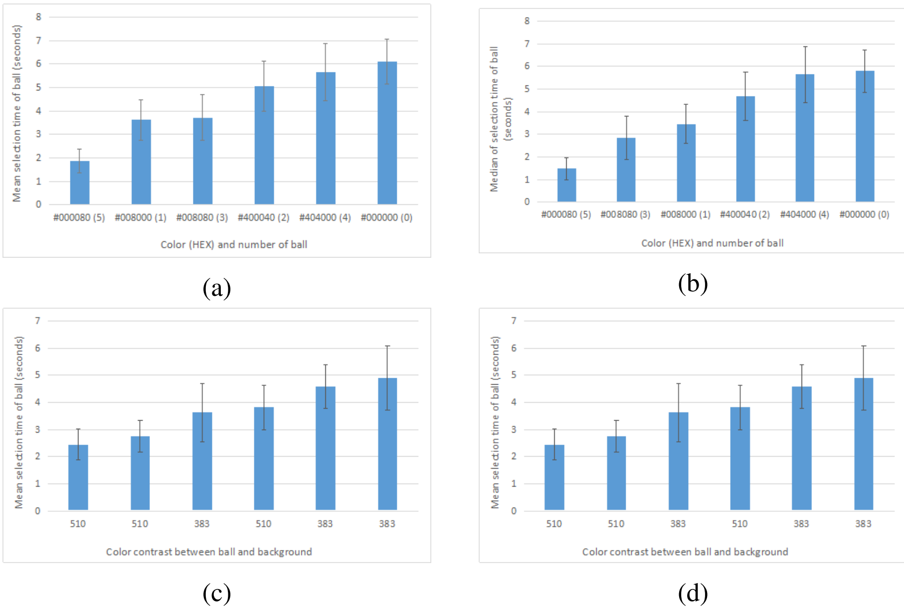
5. Results and discussion

Presentation of results was split into five parts according to the research process. In each chapter, we described results and included conclusions. Both qualitative and quantitative data have been analyzed.

5.1. Selecting objects task

In this case we took into consideration mean selection time for each object (counted from beginning of each stage), average selection order, median of these times as well as median of selection order. Mean selection times directly corresponds with mean selection order for each object. First stage included objects only with identical, low color contrast (128) with background.

Taking into account mean selection times of individual objects, we can say with 90% certainty that there is a trend which points to selecting a object with number 5 as a first one (see Figure 1). The median presented on the right chart does not confirm such trend (see Figure 1). The second stage included three objects with identical, high color contrast (510) with the background and three objects with identical, low color contrast (383). By analyzing selection times of individual objects, we can be 90% sure, that two objects with high contrast were chosen first compared to two (according to mean) or three (according to median) other



(a) (b) (c) (d)

Figure 1: Average and median of selection times of individual objects of selecting objects task (in seconds). (a) chart with average selection times in first stage, (b) chart with median of selection times in first stage. (c) chart with average selection times in second stage, (d) chart with median of selection times in second stage. Error bars represent a 90% confidence interval.

with low contrast (see Figure 1). In third stage, we included objects only with identical, high contrast (511) with background. Analysis of selection times in this stage did not confirm the trend observed in the first stage. It is worth mentioning, that all subjects completed the task successfully, without noticeable difficulties. To summarize, in accordance with hypothesis H0, we can assume with 90% certainty that in this case objects with high color contrast with background might be selected first. At the same time, we can't tell, that attention of objects with identical color contrast distributes unequally.

5.2. Observing moving objects task

In analysis of this task, we took into consideration data collected from eye-tracking using Ogama. Data exported from this software has been split into six individual csv files - each for one stage of experiment. Data from each file have been processed using D3.js library. It is worth mentioning that every file included data from all participants (excluding two of them due to inaccurate measurements).

(a) (b) (c)

Figure 2: (a) First stage of observing moving objects experiment with included summary heat map (green background was changed to white for presentation purposes). We can see, that right side with object with high color contrast with background was seen more times. (b) Second stage of observing moving objects experiment with included summary heat map. We can see, that most of the gaze points referred to objects with low color contrast with background (top-right and bottom-left of presented four objects). (c) Third stage of observing moving objects experiment with included summary heat map. We can see, that despite high color contrast of both of the objects, participants looked more times on this moving to the bottom of the screen.

According to summary heat map generated for first stage, we can assume, that object with high color contrast with background (right one) was noticed more times than this with low color contrast (see Figure 2). Analysis of second stage indicated, that most of the gaze points referred to objects with low color contrast with background (top-right and bottom-left of presented four objects) (see Figure 2).

In the third stage of an experiment, despite high color contrast of both of the objects, participants looked more times on this moving to the bottom of the screen (see Figure 2). Analysis of the fourth stage indicated, that the vast majority of subjects looked at the object with the lowest color contrast of the four objects (bottom-right) (see Figure 3). It is also worth noticing, that the bottom-left object was intensively observed only in initial state (when all objects were placed at the center of the screen). Analysis of the fifth stage, which included two objects with low color contrast with background, did not indicate any trend of observing them. Both of the objects were particularly observed in the initial state (at the center of screen) (see Figure 3). According to analysis of the sixth stage, we can notice a concentrated gaze area at the bottom of the screen, which indicates looking at a object with high color contrast with the background (see Figure 3). Also, a object (with low color contrast with the background) moving to the right edge of the screen might be observed. It is worth mentioning, that all heatmaps had circle area with point (0,0) as center. What is more, occasional negative gaze points' values have been observed. Probably it is caused by functioning of eye-tracker.

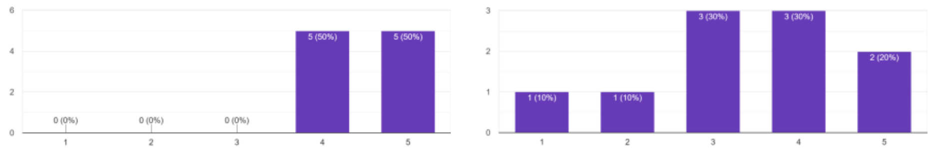
(a) (b) (c)

Figure 3: (a) Fourth stage of observing moving objects experiment with included summary heat map. We can see, that the vast majority of subjects looked at the object with the lowest color contrast of the four objects (bottom-right). Bottom-left object was also intensively observed, but only in initial state. (b) Fifth stage of observing moving objects experiment with included summary heat map. We can see, that both of the objects were particularly observed in the initial state. (c) Sixth stage of observing moving objects experiment with included summary heat map.We can notice a concentrated gaze area at the bottom of the screen, which indicates looking at a object with high color contrast with the background. Also, a object (with low color contrast with the background) moving to the right edge of the screen might be observed.

It should be also pointed out, that some participants wanted to ensure, that they cannot interact with environment during showing moving objects. The supervisor gave an appropriate, short answer. Taking into consideration analysis of each stage of this experiment, we can't be certain that object's with higher color contrast are better noticed.

5.3. Finding objects task

In this analysis, we took into consideration means and medians of finding objects times (counted from beginning of each stage as well as from previous object find). Additionally, we checked correlation between these times. In the first stage we included ten objects with low color contrast with surroundings and ten objects with high color contrast respectively. During analysis, highest and lowest values have been removed due to interfering with other data. Probably the reason was that one of participants did not know what to do (he did not understand or did not read carefully task instructions). By analyzing means and medians of finding objects times we can assume, with 95% certainty, that objects were selected in order independent of their color contrast with surroundings. What is more, in accordance with questionnaire, objects placement in virtual environment and tracking participants' decision during experiment, we can also assume, that objects were chosen sequentially with clockwise or counter-clockwise movement (see Figure 4).



(a) (b)

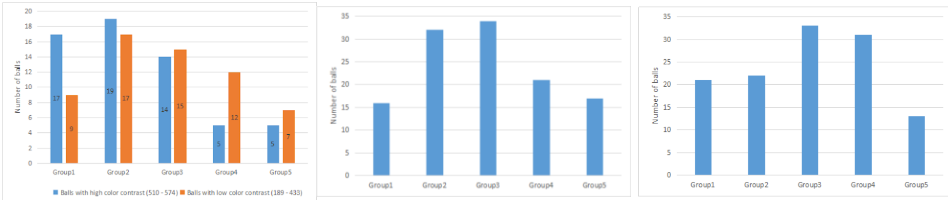
Figure 4: (a) Chart presenting answers to the statement: "I searched objects in specific order (with clockwise or counter-clockwise movement). X-axis: 1 - totally disagree, 5 - totally agree; Y axis - number of participants. (b) Chart presenting answers to the statement: "objects' contrast with surroundings made a difference in searching for them". X-axis: 1 - totally disagree, 5 - totally agree; Y axis - number of participants.

Two further stages included seventeen objects with low and high color contrast with surroundings, respectively. Results from these stages, similarly like in first stage, don't confirm relation between selection order and color contrast of objects. What is interesting, data acquired from questionnaire suggest, that color contrast of object might make a difference in searching process. Interesting fact is that almost all participants were not convinced, that they found all objects. They continued to search the scene until the end of stage. Interesting dependence has been noticed by comparing mean find times counted from the beginning of stage with these counted from previous object find. In the first and second stage, the more time counted from the beginning of the stage, the less time counted from previous object find participants needed. In case of the third stage, this correlation was reversed. In conclusion, taking into consideration all analyzed data, we can't say, with 95% certainty, that time needed for finding objects with higher color contrast is smaller than these with lower color contrast.

5.4. Grouping objects task

In this task, we took into consideration distribution of objects in individual groups, including color contrast between each of objects' halves. In order to verify hypothesis H0 standard deviation and mean difference of mentioned contrast have been calculated. To verify the second hypothesis H1 we considered selection order of objects according to color contrast between their halves. In the first stage, six objects with high color contrast and six objects with low color contrast have been analyzed.

Taking into account data from the chart, we can observe, that none of five groups did not remain empty (see Figure 5). Distribution of objects' color contrast

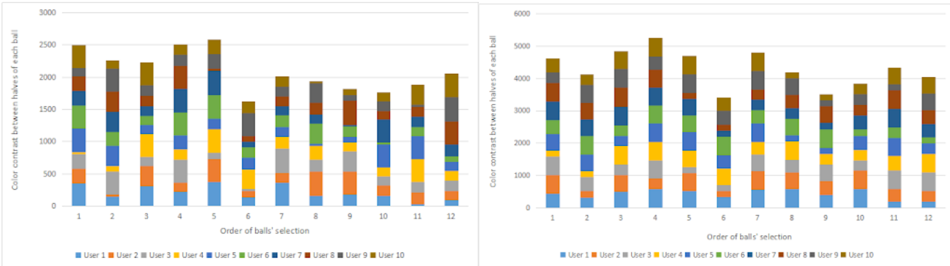


(a) (b) (c)

Figure 5: (a) High vs low base contrast between objects' halves in each group in the first stage of task. (b) Distribution of objects with high contrasts between halves in the second stage of task (base contrast). (c) Distribution of objects with low contrasts between halves in third stage of task (base contrast).

is unequal - in the first group definitely high contrast (eight objects difference) prevails, in fourth group objects with low color contrast (seven objects difference) prevails, whereas in other groups differences are small. Interesting case may be observed in charts presenting mean difference of objects' contrasts in each group. In groups 2 and 3 where we observed small difference between number of objects with low and high contrast (one - two objects), there is also small difference in contrasts' values. In group 5 color contrasts difference was undisputedly the highest. It is worth noticing, that differences between base color contrast and the one calculated by using masks were correlated. In the second stage of an experiment, only objects with high color contrast between their halves have been included. An important fact is that contrast values are relatively close to each other (maximum difference of contrast - 135). By analyzing data from this stage of the task, we can state, that objects were grouped unequally, with most of them being assigned to groups 2 and 3 (see Figure 5). The third stage of this task included objects with low color contrast between their halves. Similarly, like in the previous stage, objects were grouped unequally. Most of them were in groups 3 and 4 (see Figure 5). During verification of hypothesis H1 (connected with selection of objects), we noticed tendency of selecting objects with higher contrast first. It is worth noticing, that this tendency is more noticeable in analysis of color contrast calculated from mask, than base color contrast (see Figure 6). Analysis of other two stages did not show any tendency.

According to presented analysis, it can't be certainly said, that object's with similar color contrast are also perceived similarly. This is demonstrated by the distribution of objects of all five groups, despite the relatively small differences in contrasts (second and third stage). In case of first stage analysis in terms of color contrast level, as well as differences between values of contrast between halves of each object also did not prove any grouping tendency. Verification of order of



(a) (b)

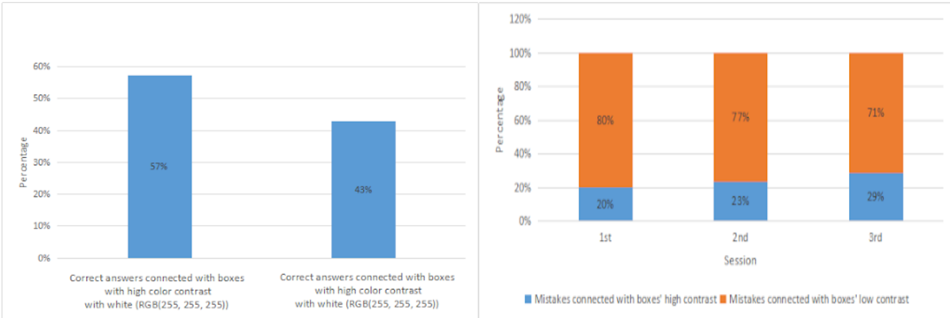
Figure 6: Assignment order of objects in first stage of objects grouping experiment along with specified users. (a) color contrast between halves of each object calculated according to base colors, (b) color contrast between halves of each object calculated according to colors from mask.

objects' selection showed tendency only in the first stage of experiment. We took into consideration both base contrasts and these calculated including light on scene (by using mask method). In this case, it can't be certainly said that objects with higher color contrast are selected as first. It is worth pointing, that considering data collected from questionnaires we can assume, that color probably had influence on assigning objects to groups. It can be also said, that color contrast between objects and surroundings probably did not matter in terms of perceiving objects, what can be proven with data collected both from virtual environment and questionnaires.

5.5. Objects remembering task

Last of the analyzed task is this, referring to remembering texts on colored boxes (also named as cubes). During data analysis, we took into consideration the number of both incorrectly and correctly selected boxes. Division was made with a distinction of these with low and high color contrast with white (RGB(255, 255, 255)) background. What's important, analyzed color was connected with boxes in the first stage, not those pointed in the second one. Additionally, assignment order of colors to individual cubes have been verified.

Data analysis for the first assumption of the hypothesis (color contrast of boxes in correct answers) did not show major advantage of answers connected with boxes with high color contrast over these with low color contrast (see Figure 7). The data on the second part of the hypothesis (color contrast of boxes in wrong answers) are definitely more interesting. In each of three stages we observed, that majority of answers relates to boxes with assigned color with low color contrast with white (RGB(255, 255, 255)) background (see Figure 7). Overall result for all stages (75% - answers with low color contrast, 25% - answers with high color contrast)



(a) (b)

Figure 7: (a) Correct answers distribution divided into answers connected with boxes having high color contrast and low color contrast with white (RGB(255, 255, 255)). (b) Wrong answers distribution divided into answers connected with boxes having high color contrast and low color contrast with white (RGB(255, 255, 255)).

confirms this trend. During analysis of order of colors' assignment we noticed, that in all cases color selected first had high color contrast with black (RGB(0, 0, 0)) panel. Verification of all results did not indicate direct correlation between color contrast and assignment order (see Figure 8).

Taking into account verification of both correct and wrong answers, we can assume, that color contrast influences objects remembering. According to analysis of assignment order of each color, it can't be said, that colors with higher color contrast are selected first. It's worth noticing, that conducting this experiment with higher number of participants may give interesting results.

6. Conclusion

Prepared research environment consisting of five individual experiments allowed for analysis of color (especially its contrast) impact on objects perception in virtual space. Within a few days, fifteen participants took part in the research. Both quantitative data from virtual environment and qualitative data from questionnaires have been acquired. Results from box remembering task might suggest, that there is a correlation between high color contrast and memorization efficiency. We can't be certain, that colors having high contrast with surroundings are selected first and better noticed by humans. Verification of color contrast influence on its selection speed did not give clear results. Further research is needed in case of perceiving objects with similar color contrast. More accurate results may be achieved by implementing more homogeneous virtual environments, with minimized range of

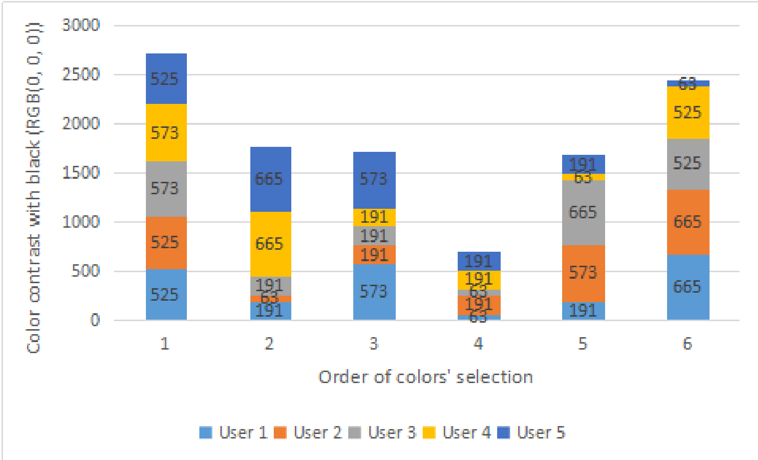


Figure 8: Assignment order of colors including their contrast with black (RGB(0, 0, 0)) panel. Colors on bars represent individual users.

participant's motion. Proposed experiments can be an incentive to further research in this field.

References

[1] Soranzo, A. *Simultaneous color contrast*, pages 1149–1152. Springer New York, New York, NY, 2016. ISBN 978-1-4419-8071-7. doi: 10.1007/978-1-4419-8071-7_268. URL `https://doi.org/10.1007/978-1-4419-8071-7_268`.

[2] Lewandowska, A., Samborska-Owczarek, A., and Dzisko, M. Contrast perception across human cognitive style. In A. Campilho, F. Karray, and B. ter Haar Romeny, editors, *Image Analysis and Recognition*, pages 345–352. Springer International Publishing, Cham, 2018. ISBN 978-3-319-93000-8.

[3] Roberts, P. An ecumenical response to color contrast cases. *Synthese*, 194(5):1725–1742, 2017.

[4] Shapiro, A. Separating color from color contrast. *Journal of vision*, 8:8.1–18, 2008. doi:10.1167/8.1.8.

[5] Ratnasingam, S. and Anderson, B. L. What predicts the strength of simultaneous color contrast? *Journal of Vision*, 17(2):13–13, 2017. ISSN 1534-7362. doi:10.1167/17.2.13. URL `https://doi.org/10.1167/17.2.13`.

[6] O'Shea, R. P., Brini, S., and Wade, N. J. Ragona-scinà's (1847) method for, and observations of, simultaneous color contrast. *i-Perception*, 7(2):2041669516643239, 2016. doi:10.1177/2041669516643239.

[7] Pelet, J.-E. and Taieb, B. Effects of colored contrast of mobile websites on behavioral intentions. In *Conference: CARMA 2016 - 1st International Conference on Advanced Research Methods and Analytics*. 2016. doi:10.4995/CARMA2016.2016.3110.

[8] Souza, G., Miquilini, L., Brito, F., Herculano, A., and Lacerda, E. Variegated mosaic stimulus combining luminance and color contrasts for visual evaluation. *Anales de la Asociacion Fisica Argentina*, 29(Especial InVision):7–10, 2018. doi:10.31527/analesafa.2018.inVisionT.7.

[9] Hernández-Andrés, J., Romero, J., Nieves, J., and Lee, R. L. Color and spectral analysis of daylight in southern europe. *Journal of the Optical Society of America. A, Optics, image science, and vision*, 18 6:1325–35, 2001.

[10] Ma, Y.-F. and Zhang, H.-J. Contrast-based image attention analysis by using fuzzy growing. In *Proceedings of the Eleventh ACM International Conference on Multimedia*, MULTIMEDIA '03, page 374–381. Association for Computing Machinery, New York, NY, USA, 2003. ISBN 1581137222. doi:10.1145/957013.957094. URL `https://doi.org/10.1145/957013.957094`.

[11] Tregillus, K. and Webster, M. A. Dynamics of color contrast adaptation. *J. Opt. Soc. Am. A*, 31(4):A314–A321, 2014. doi:10.1364/JOSAA.31.00A314. URL `http://josaa.osa.org/abstract.cfm?URI=josaa-31-4-A314`.

[12] Hryniewska, W. *Ruch gałek ocznych, uwaga i komfort w rzeczywistości wirtualnej. Rola jasności, koloru i kontrastu w postrzeganiu i zapamiętywaniu*. Master's thesis, Politechnika Łódzka, 2018.

[13] Livatino, S. and Hochleitner, C. *Simple Guidelines for Testing VR Applications*, chapter 18, pages 289–310. InTech, 2008. ISBN 978-953-7619-15-2. doi:10.5772/5925.

[14] W3C. `https://www.w3.org/`, accessed 2021-06-01.

[15] W3C. Techniques For Accessibility Evaluation And Repair Tools. `https://www.w3.org/TR/AERT/`, accessed 2021-06-01.

[16] OpenGazeAndMouseAnalyzer, O. An open source software designed to analyze eye and mouse movements in slideshow study designs. `https://www.ogama.net`, accessed 2021-06-01.

[17] D3.js Graph Gallery. https://www.d3-graph-gallery.com/graph/density2d_shading.html, accessed 2019-09-21.

[18] D3.js. https://d3js.org/, accessed 2019-09-21.

[19] Bednarski, R. *Ocena czytelności tekstu ekranowego i doboru jego parametrów*. Ph.D. thesis, Politechnika Łódzka, 2010.

[20] W3C. Basic Data Types and Interfaces. https://www.w3.org/TR/2003/REC-SVG11-20030114/types.html, accessed 2021-06-01.

[21] Tribe, T. E. https://theeyetribe.com, accessed 2021-06-01.

[22] Tobii. https://gaming.tobii.com/, accessed 2019-07-09.

[23] Unity. https://unity3d.com, accessed 2021-06-01.

[24] Microsoft. Visual Studio. https://visualstudio.microsoft.com/, accessed 2021-06-01.

[25] Tullis, T. and Albert, W. *Measuring the User Experience: Collecting, Analyzing, and Presenting Usability Metrics*. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA, 2008. ISBN 0123735580.

[26] Sauro, J. and Lewis, J. R. *Quantifying the User Experience, Second Edition: Practical Statistics for User Research*. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA, 2nd edition, 2016. ISBN 0128023082.