An Elegant Experimental Setup for Accurate Presentation of Dichoptic Stimuli

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***Abstract*—We present an end-to-end system for dichoptic stimuli presentation and response capture. The lower bound for the inter-stimulus interval of the proposed system is approximately 17 ms. The efficiency of the proposed system is demonstrated using a match-to-sample (MTS) paradigm for measuring the reaction time of 29 males aged between 18 and 22 years and 29 females aged between 19 and 22 years in matching three unique hues, namely red, blue, and green. Using VR glasses ensures that the perception of the colours determined by the three attributes of hue, brightness, and saturation is precisely controlled across trials and subjects, independent of the ambient lighting. It is observed that males have around 16% shorter reaction time than females (p <0.001). Understanding sex differences in the time taken to match colours helps in a more accurate interpretation of results in studies on sex differences in cognition that use colours. It also helps better understand the disease process of neurological disorders affecting visual perception that manifest differently in males and females. The Android code for the entire system is available as open-source code.**

***Index Terms*—sex-difference, dichoptic, VR glasses, amblyopia, colour perception**

I. Introduction

The word "dichoptic" is derived from two Greek words "dicha" and "optikos" meaning "in two" and "vision", respectively. Dichoptic presentation facilitates simultaneous stimulation of both eyes with separate and independent stimuli. Nicholas J. Wade argues in his recent work [1] that the term initially used for this type of stimulus presentation was "dichopic", in line with the words "dichotic" and "dichorhinic" in audition and olfaction, respectively, but was changed to "dichoptic" over time [2].

Currently, dichoptic stimuli is used for characterising interocular suppression [3] and binoucular balance [4], for perceptual training [5], [6], for oculomotor training [7], for quantifying aniseikonia [8], for assessing binocular central visual field and eye movements [9], for characterising the visual deficits associated with amblyopia [10], for studying sensory eye dominance (SED) [11], for studying adaptation to chromatic light [12], for studying the effect of Parkinson's disease (PD) in oculomotor function [13] etc.

Primarily, the following five systems are currently used for dichoptic presentation:

1) stereoscopes with regular video displays [14],
2) head-mounted displays [3],
3) polarized glasses with 3D video displays [4],
4) anaglyph glasses with regular video displays [8] and
5) active shutter glasses with compatible high refresh rate video displays. [15]

These systems have one or more of the following limitations:

- Anaglyph glasses, although cheap, are not colour neutral and hence do not allow dichoptic stimuli presentation in the full colour spectrum.
- Polarized glasses have narrow viewing angles and require a compatible external display such as a 3D-compatible monitor or a projector.
- Active shutter glasses require an external display of high refresh rate, with which it needs to be synchronized for proper functioning.
- Head-mounted displays are expensive.
- The display in most of the devices is affected by the ambient light.
- A conventional stereoscope requires a chin and headrest to constraint the head movement of the participant, which can often be unconformable for the participant.

In this paper, we present a novel end-to-end system for dichoptic stimuli presentation. The proposed system consists of VR (virtual reality) glasses, two mobile phones running two custom Android applications for stimuli presentation and response capture and a Python script for calculating the response time. The advantages of the proposed system are listed below:

- Unlike a stereoscope, there is no need to constrain the head movements of the participant. This is because the left and the right visual fields are completely separated, even if the participant moves his or her head or eyes.
- The ambient light does not affect the stimuli presented. This eliminates the need for any specialized room for conducting the dichoptic experiments.
- VR glasses are only slightly costlier than anaglyph glasses. Any Android mobile phone, which is ubiquitous these days, can be used in the system. The script for calculating the response time is written in Python and hence no proprietary software is required.
- The system does not require any specialized display like a 3D monitor.

- The proposed architecture can capture the response time of the participant with an accuracy of 1 ms which is limited by the touch-sampling rate of the system.
- The proposed system works entirely on battery and is thus highly compact and portable.
- The inter-stimulus duration can be as low as 17 ms.

One of the applications of the proposed system is large scale screening of disorders such as amblyopia. An ideal system for this scenario should be 1) Cost-effective, 2) Compact and portable, 3) Should run on batteries, 4) Setting up of the system should be simple, 5) Requirements of other facilities or system other than the dichoptic presentation system, such as dark-room and chin-rest should be minimal.

Along with the details of the proposed system, we also present the results of a dichoptic experiment which used the proposed system for stimuli presentation. In the study, we investigate whether there is any sex-difference in the reaction time in a colour matching task. It is well-known that there are some level of sex differences in the auditory [16], olfactory [17], [18], somatosensory [19], gustatory systems [20]. Although sex-difference in colour perception has already been reported in the literature, the results are contradictory. This is primarily because of flaws in some of these experiments. For instance, in the study by Jain et al. [21], the experiment was performed outdoor in sunlight from noon to 3 pm. The authors have not reported any compensation for the changes in the lighting that would have happened during the span of the experiment. The results by Jain et al. contradict the findings of Miranda [22] and Donahue et al. [23], although there are similarities between the objectives and the experimental protocols.

II. Materials and Methods

A. Experimental protocol

Data collection was based on two experimental protocols, both following dichoptic stimuli presentation paradigm. The protocols are designed following the tenets of the Declaration of Helsinki and written informed consent has been obtained from all the participants, who also received monetary compensation for their participation. The protocols are approved by the Institute Human Ethics Committee (IHEC) of the Indian Institute of Science, Bangalore, India (IHEC Approval No: 17/20200821).

The experimental protocol is a match-to-sample task requiring a dichoptic stimuli presentation system and a response capture system. The stimuli presentation system includes a pair of VR glasses and an Android mobile phone running a custom Android application and the response capture system (RCS) is again an Android mobile phone running another custom Android application. Different screens in the protocol are described below:

- **Target screen:** Each trial started with the target screen. In this, one of the target colours (red, green and blue) was presented simultaneously to both the eyes (binocular presentation) for a duration of 2 s. These three colours were chosen because these colours are both unique hues and primary colours of light [24], [25] and are the most commonly used colours in the studies on colour perception [26]–[28]. Also each channel in an RBG colour space in a digital image corresponds to one of these colours.
- **Masking Screen:** A black backward masking screen was presented for a duration of 3 s to reduce any possible after-image effects, which might affect the effective duration of stimulus presentation [29].
- **Stimulus Screen:** In this screen, distinct colours were presented to the two eyes (dichoptic presentation). In 50% of the trials, one of these was the target colour. Also, all the target colours were equiprobable. The duration of the stimulus was 50 ms.
- **Screen During Response Capture:** A black screen was presented for a duration of 2 s, during which the participant could record his/her response using the handheld mobile phone.

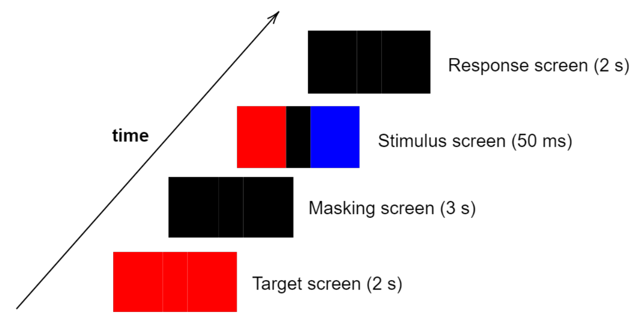

Fig. 1: Different screens in the match-to-sample task employed in this work. The target screen informs the participant of the colour to look for (sample stimulus) in the stimulus screen (stimulus to match). A black masking screen is used to avoid any after-image effect.

The different screens in the match-to-sample task is given in Figure 1.

The details of the two protocols are given below:

- **Protocol A:** In this protocol, the subject needed to press the button in the mobile phone of the response capture system if one of the two colours displayed in the stimulus screen was the same as the one displayed earlier in the target screen. The mobile phone for recording the responses was given to the right hand of the participant.
- **Protocol B:** Protocol B was similar to the protocol A, except that the mobile phone for recording the responses was given to the left hand of the participant. There were two major reasons for separating protocols A and B:
  1) To counterbalance any possible effect of the hand used for registering the response.
  2) To increase the number of trials of the experiment. Splitting the 120 trials into two sessions of 60 trials each helped the participant to be better focused during the experiment and reduced the fatigue.

B. *Dichoptic stimuli presentation and response capture system*

1) Stimulus Presentation System: The hardware of the stimulus presentation system consists of a Shinecon G04A VR glasses and Realme C2 Android phone having 15.59 cm HD+ display. The resolution of the display is 720×1560 pixels and the pixel density is 282 ppi. The refresh rate of the display is 60 Hz. That is, the display is capable of displaying new stimuli every 17 ms. For presenting the stimuli, custom Android applications is used, details of which are given later in this section. Timestamps of stimuli were recorded along with other details such as the side to which the stimulus was presented.

2) Response Capture System: The subject's response is captured using another Android mobile phone (Redmi 7A), which also has a custom Android application. The Android application has a single button covering the entire screen of the mobile phone for ease of use. If the button is pressed, the device vibrates, letting the participant know that the button-press has been recognized; this avoids multiple presses of the button, although during data analysis, we have implemented an algorithm to detect and discard stray button presses.

3) Software components: Both the stimulus presentation and the response capture systems employ custom Android applications. One challenge in the development of the system was to develop a mechanism to accurately capture the response with minimum latency. The fact that the mobile phone for presenting the stimulus resides inside the VR box reduced the number of options we have for capturing the response using the stimulus delivery system itself. Use of wireless devices such as Bluetooth devices lead to high latency, which reduces the accuracy of the response capture system. To mitigate these issues, we decided to use one more mobile phone for response capture. The two mobile phones are independent. The two mobile phones write the timestamps of the stimuli and responses in separate text files. The reaction time is the difference between the two timestamps. For this setup to give satisfactory accuracy, the times in both the devices need to be synchronized. This is achieved using TrueTime library (https://github.com/instacart/truetime-android). This library requests a time seed from an NTP (Network Time Protocol) server and this seed is cached in the device. The library compensates for the round-trip time involved in getting the seed from the server. The seed needs to be requested only once after booting the device, since it is cached. Thus, subsequent network requests are avoided. The library requests multiple NTP servers at once and filters out the best response received. For a mobile phone with a display refresh rate of 60 Hz, the inter-stimulus interval can be as low as 17 ms. The Python script for calculating the response time can be downloaded from http://mile.ee.iisc.ac.in/downloads.html.

C. *Participants for the Study*

The data for the study was collected in two phases. In the first phase of the study, eight male and eight female subjects participated. They were required to press a button as fast as possible if one of the dichoptically flashed colours was the same as the colour binocularly presented before. Twenty four male and twenty three female subjects participated in the second phase. All the participants had normal near and far visual acuity. None of the participants had any prior experience with VR glasses. Colour vision of all the participants was tested using 38-plates Ishihara colour blindness test and the handedness of the participants was tested using Edinburgh Handedness Inventory test. All the participants had one training session where they viewed the experiment directly on the mobile phone (without VR glasses) and registered their responses using the other mobile phone.

TABLE I: Summary of various experimental protocols in this study. (RCS: Response capture system)

Protocol	Subjects	Paradigm	Remarks
A	29 females and 29 males	Match-to-sample	RCS in right hand
B	20 females and 17 males	Match-to-sample	RCS in left hand

The details of the participants in each phase of data collection are given below:

- **Phase 1:** Sixteen participants (eight each of males and females) aged between 19 and 21 years ($\mu = 20.56, \sigma = 0.73$) were recruited in this phase. The mean ages of the male and the female participants were 20.63 ± 0.74 and 20.50 ± 0.75 years, respectively.
- **Phase 2:** Forty seven subjects (24 males and 23 females) aged between 18 and 22 years ($\mu = 20.62, \sigma = 1.28$) were recruited in the second phase. The mean ages of the male and female participants were 20.46 ± 1.44 and 20.78 ± 0.74 years, respectively. Data of two male and one female participants were discarded since their Edinburgh's Handiness scores were less than 75. The data of another male and two female participants were discarded since the participants dozed off during at least one of the experiments.

The mean accuracy is 99.5% with almost all the participants achieving 100% accuracy. Only the correct responses were used for calculating the reaction times.

The details of the number of subjects who participated in each protocol are given in Table I. The protocol A had more number of participants due to two reasons:

1) In phase 1, data was collected based only on protocol A. Thus, all the participants had the mobile phone for registering their response on their right hand and no control protocols were there.
2) The participants had an option to withdraw from the data collection at any point in time. Some of them quit after the data collection based on protocol A.

III. Results

A. *Effect of sex and age*

For the analysis of the effect of sex and age, the reaction times of the two experiments following protocol A and B are averaged for participants who participated in both experiments and the reaction time of the experiment following protocol A alone is considered for participants who participated only in the experiment following protocol A. Therefore, we have the data from a total of 29 females and 29 males. For analysing the effect of age, the participants are divided into two groups; group 1 consists of participants who age is less than 21 years and group 2 consists of participants whose age is 21 years or more. 21 years is chosen as the cutoff since 21 is the meadian age of all the participants in the study. The reaction times are normally distributed as determined by Shapiro-Wilk test for normality.

A two-way ANOVA (SEX X AGE))showed no significant SEX by AGE interaction [$F(1, 54) < 0.80; p > 0.41$] and no main effect of AGE [$F(1, 54) < 1.50; p > 0.23$]. The effect of SEX was significant [$F(1, 54) = 13.20; p < 0.001$]. The mean reaction time for females is 749 ms whereas for males, it is 621 ms. The difference between the reaction times of females and males is 128 ms.

B. Effect of eye visual field

Similar to the analysis on the effect of age and sex, the reaction times are averaged if the participant has participated in both the experiments. Data from a total of 29 females and 29 males are considered for this analysis.

The mean reaction time of male participants is 611 ms when the stimulus is presented to the left eye whereas it is 633 ms for the right eye. In the case of female participants, the mean reaction time is 726 ms for the left eye and 760 ms for the right. Despite left eye being faster in the case of both sexes, a two-tailed independent Student's t-test revealed that the effect of field of vision (left or right visual field) on the reaction time is not statistically significant for females [$t(56) < 0.73, p > 0.46$], males [$t(56) < 1.05, p > 0.29$] and females and males combined [$t(114) < 1.14, p > 0.12$].

C. Effect of hand

For analysing the effect of the hand used to register the responses on the reaction time, we selected the subset of subjects who participated in both protocols. A total of 37 participants (20 females and 17 males) participated in both protocols. The handedness score measure using Edinburgh Handedness Inventory test is 97.4 ± 6.0. The mean reaction time for Protocol A (RCS in right hand) is 694 ms and Protocol B (RCS in left hand) is 688 ms. A two-tailed independent Student's t-test showed no statistically significant difference in means [$t(72) < 0.25, p > 0.40$].

The mean values of reaction times under various conditions are shown in Figure 2.

IV. Discussion

A. Effect of sex and age

The observed effect of sex is statistically significant. It is also significant in relative terms since the observed time difference of 121 ms corresponds to a difference of 16%. This is clearly in line with the observation of McGivern et al. [26]. We put forward three possible explanations for this observation:

- First, it is possible that the observed sex-difference is only because of the fact that men in general have shorter reaction time [30]. Even if this is true, it does not diminish the need for consideration of this sex-difference in the design and interpretation of cognitive experiments that involve colour perception.
- The second plausible explanation for the sex-difference in colour perception is based on the evolutionary theory for sex differences. In the early hunter-gatherer society, men and women played sex-specific roles: men were primarily hunters and women were gatherers. Their role required men to be able to identify and categorize prey or predators faster [28], [31], [32]. Being able to perceive colours faster might have helped them in their role as hunters. This explanation is in line with the evolutionary theory for sex differences in spatial tasks proposed by Rick O'Gorman [33] and the observations of Hurlbert and Ling in the rapid paired comparison task [34]. Testosterone concentration also affects spatial abilities [35]. The comparatively high concentration of testosterone in males may lead to better visuospatial abilities which may also include any subtle change in the position of any object in the visual field.
- The third plausible explanation for the observed sex difference is based on the studies on rodents and non-human primates. Studies in rhesus monkeys have shown that a high number of androgen receptors are found on neurons in the visual cortex [36]. Similar observations have been made on rats also [37]. Androgen receptors are known to reduce the post-natal apoptosis of neurons in the visual cortex, leading to around 20% more number of neurons in the visual cortex of males than females [38], [39]. As suggested by Doncarlos et al. in [40] and by Abramov et al. in [28], this observation might be common across all mammalian species including human beings. Hence, the observed sex difference might be because of endocrinological sex differences in human beings.

Though we are unable to give a confirmed explanation for the observed sex-difference, the fact that the observation is in line with other studies in the literature validates the efficacy of the proposed system. Further studies are required to zero-in on a possible explanation.

B. Effect of eye visual field

Several works have shown that there is significant right ear advantage (REA) for human beings when processing certain types of auditory inputs [41], [42]. Though one might expect a similar advantage for eyes in the perception of colours, we have shown that it is absent in the human visual system. The auditory cortex represents different sound frequencies in columnar organization, while the visual cortex has blobs representing colors. Neural representation of sound begins in the inner ear, while colors are represented in the visual cortical areas. This very difference between processing at an early level (in the case of sound) and at a later level (in the case of colors) may justify our findings. Though there is hemispheric

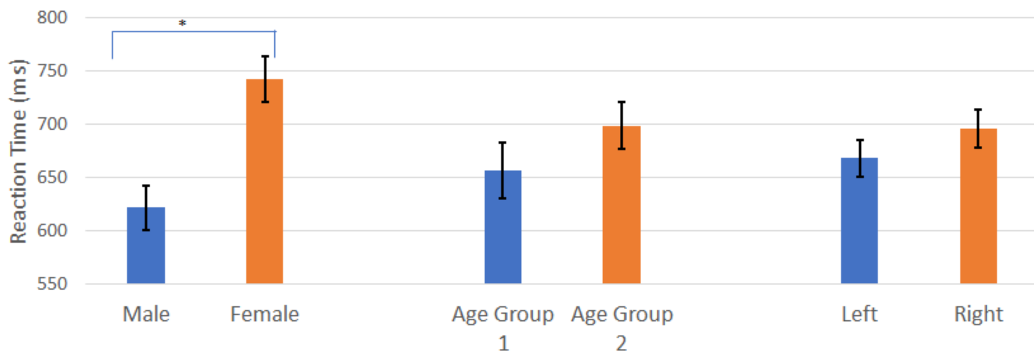

Fig. 2: The mean values of reaction time. "Male" and "Female" denote the conditions where the responses of male and female participants are considered separately for calculating the mean values. "Age Group 1" and "Age Group 2" respectively denote the conditions where the responses of participants whose age is less than 21 years and who age is 21 years or more is considered separately for calculating the mean values. "Left" and "Right" denote the conditions when only the responses to the stimuli presented to the left or right eye field of vision are used to calculate the mean values of the reaction time. Error bars represent standard errors. Statistically significant difference at 95% confidence interval is denoted by *.

separation in processing the auditory inputs from the two ears in the absence of corpus callosum, the visual inputs from both the eyes reach both the hemispheres even in the absence of corpus callosum through the optic chiasma. The absence of any significant difference can also be because of "dichoptic balance" [43].

V. Effect of hand

Since all the participants in this study are right-handed, an advantage for right hand in reaction time could be expected. Contrary to this expectation, we did not find any significant difference in the reaction times when left and right hands were used for registering the response. This observation is in line with the results reported by Nisiyama and Ribeiro-do-Valle [44]. This might be due to the fact the responses required in our experiments are not complex enough to reveal the dominance of left hemisphere.

VI. Limitations of the current study on sex-difference in colour perception

The following are the major limitations of the current study:

- It does not incorporate any control study, without which it is difficult to ascertain the reason for the observed colour difference.
- The differences in the sensitivity of photoreceptor cells to different colours are not accounted in this study.
- The reduction in accuracy due to the touch-sampling rate of the mobile phone in RCS is not accounted for in this study.
- It is better to use different shades of brown rather than the primary colours for validating the hunter-gatherer hypothesis since animals typically have colours in the shades of brown.
- The same experiment could be done without a dichoptic experimental paradigm. The dichoptic experimental paradigm was introduced to validate the efficacy of the proposed system.

In spite of these limitations, the observed sex-difference is large and statistically significant to be ignored.

VII. Conclusion

In this paper, we have presented an end-to-end system for dichoptic stimuli presentation and response capture. The system can display stimuli at a rate of 60 stimuli per second. Using this proposed system, we have reproduced the results of two studies in the literature. In line with the results of McGivern et al., we have shown that there is a male advantage in colour perception and in line with Nisiyama and Ribeiro-do-Valle [44], we have shown that difference in the mean reaction times when left and rights hands are used for registering response are not statistically significant. The proposed system can be used for various clinical applications such as for studying the effects of various neurological disorders such as amblyopia and Parkinson's disease (PD) on vision, characterizing the neural correlates of various phenomena such as binocular rivalry. Since the whole setup is compact and highly portable (works entirely on battery unlike specialized display devices such as 3D projectors), this can be used for large-scale screening of various disorders. The fact that the proposed system is an end-to-end system with high accuracy, it can be used in various experimental paradigms.

More than offering an interesting difference between males and females, the results on sex-difference in visual perception also warrant the use of sex as a control variable in the design and analysis of cognitive studies involving colour perception [30]. Also, many neurological disorders manifest differently based on sex. For instance, the premorbid conditions of schizophrenia are less severe for women than men [45]. Schizophrenia is also associated with abnormal visual perception [31] and understanding the sex differences in visual perception can help in deciphering the disease process.

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