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The effects of colour attributes on cognitive performance and intellectual abilities in immersive virtual environments

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ABSTRACT

It is known that well-designed immersive Virtual Reality (VR) environments can positively impact on user experiences, with results evidencing that a considered approach to hue design can trigger positive cognitive performance and intellectual abilities. However, limited research has been conducted to study the design potential of chroma and brightness colour attributes of immersive VR environments. This study investigates the impacts of colour attributes on cognitive performance and intellectual abilities in immersive Virtual Reality (VR) Environments. The paper included the results of two psychological experiments that evaluate people's cognitive performance to different chroma and brightness, respectively. The experiments further studied effects of colour attributes on participants' logical and lateral thinking abilities, as well as their attention to details. Participants' response time and error rate when completing each psychometric test were recorded with different hue, chroma, and brightness backgrounds in immersive virtual environments. The data collected from participants reveal the differential impacts of colour attributes on people's cognitive performance and intellectual abilities in immersive VR environments. The findings of our study provide new insights to metaverse areas of research suggests that effective use of colour design in the immersive digital context can positively trigger people's cognitive performance and intellectual abilities at an unconscious level.

Credit author statement

Guobin Xia, Phil Henry, Francisco Queiroz and Stephen Westland: Conceptualization, Methodology; Guobin Xia and Qian Cheng: Software; Guobin Xia and Yun Chen: Data curation; Guobin Xia, Phil Henry: Writing- Original draft preparation. Guobin Xia: Visualization, Investigation. Phil Henry, Francisco Queiroz and Stephen Westland: Supervision. Guobin Xia: Software, Validation. Guobin Xia, Stephen Westland, Phil Henry and Yun Chen: Writing- Reviewing and Editing.

1. Introduction

Previous literature relating to VR or immersive experience design has centred on recognizing the potential for VR to introduce new digital experiences to positively impact human lives. Existing areas of research largely around one of just a few key topics such as therapy-based aversion treatments, education, architecture, gaming, and marketing (Bracq et al., 2019; Hayes & Johnson, 2019; Hock et al., 2017, pp. 4034–4044; Li & Xu, 2020). Growing scholarly interest began in how well the immersive VR experience is fully understood and whether there are greater possibilities to further explore in its design potential (Xia et al., 2021a, 2021b). Using colour to prompt the design of products and environments in real word is not a new idea. However, the question 'How to use certain colours?' remains a current issue. It is known that every colour can be described with its three main attributes, which are hue, chroma (saturation) and brightness (value) (Burns & Shepp, 1988; Munsell, 1912; Wilms and Oberfeld, 2018b). Humans use hue to know which colour is being viewed, by which a sample is recognised as, for example, 'blue', 'red' or 'green'. Chroma refers to how pure or vivid the hue is in comparison to a neutral grey of the same value; in other words, a colour with high saturation has less grey in it. Lightness is the third dimension of colour, and this concerns the brightness or darkness of a colour as it relates to light and dark (Stauffer et al. (2014). Most research on colour psychology has investigated the influence of hue on people's psychological and physiological responses on people's psychological and physiological responses. For instance, numerous findings have

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revealed a well-defined connection between human emotions and certain colours (burkitt & sheppard, 2014; lee and lee, 2006; Ou, 2012; Ou, Luo, Woodcock, & Wright, 2004). The associations that result from the IF visual process regarding colour psychology link colour categories to subjective responses (e.g. yellow, red – warmth and excitement) (Ou, Luo, Woodcock, Wright, Et Al., 2004; Jacobs et al., 1975; Valdez & Mehrabiana, 1994), and those connected to the NIF visual process can produce physiological reactions, including in blood pressure, heart rate, respiration, GSR, and EEG power, which manifest in emotional experiences (e.g. arousal effects) (Gerard, 1958; Jacobs and Hustmyer, 1974; Westland et al., 2017). Nevertheless, it is still uncertain as to whether IF or NIF visual systems affect emotional changes in relation to colour (Westland et al., 2017). Other empirical studies regarding colour psychology have comparatively divided human emotional responses to colour into three levels: unconscious, semiconscious and conscious (Lee and Lee, 2006, Kauppinen-Räisänen, 2014). The first level, unconscious response, refers to innate response, which includes biological responses and those associated with subjective unconscious memories. It is suggested that the unconscious consequences of emotional colour responses can serve as valued triggers in health management, presently recognised as 'colour therapy' (O'connor and Application, 2011; Green and Care, 2005). The second level, semiconscious response, is referred to as culturally learned response (Kundu, 2010), which correlates with learning rather than instincts. Clearly, semiconscious response can be ingrained in people's daily behaviour patterns, which are passed on from parents to children (Lee and Lee, 2006). The third level of emotional responses to colour is conscious, which can be explained as personal colour preferences based on individual experiences, including income, educational background, sophistication and personal exposure (Kopacz, 2004). No matter the cause of colour emotions, they are crucial in many areas, such as marketing (Amsteus et al., 2015), retail (Ares & Deliza, 2010), art (Gage, 1999) and design (Jiang et al., 2020), but have been less studied in VR-related research. With regard to immersive VR technology, it is certain that emotion plays an important role in the sense of presence and level of immersion (Baños et al., 2004; Lombard & Ditton, 1997; Lombard et al., 2000). A limited understanding of colour emotions or cognitive performance in the design of immersion and engagement suggests that more research is needed on the design potential of colour to create positive immersion for VR systems. In the research on colour stimulations and arousal, emotions and cognitive performance, an important theory attempts to explain the empirical relationship between arousal and cognitive performance, the U-shaped relationship, initially established by Yerkes and Dodson and known as the Yerkes–Dodson Law (Yerkes, 1908). The Law states that raised levels of arousal can enhance performance up to a certain point; however, beyond an optimum, increasing arousal is followed by a decline in performance (Russell et al., 1974). For example, an optimal level of stress before an exam can increase your attention on the test and help retain the knowledge you have attained, while excessive test anxiety can weaken your ability to focus and make it more difficult to remember certain answers (Jamieson et al., 2016).

Nevertheless, the dimensions of chroma and brightness have rarely been explored for more understanding of their effects on people's emotions and cognitive performance. Chroma (or saturation) is a continuous dimension range from high to low pigmentation. Higher-chroma colours are more vivid and stand out more than lower-chroma colours. On the basis of this trait, previous studies suggest that an increased level of chroma can influence arousal and lead to a decrease in calmness (Valdez & Mehrabiana, 1994). Furthermore, some studies show that the chroma level of colour stimuli has a stronger influence on arousal state than hue (Gao et al., 2007; Suk and Irtel, 2010; Duan et al., 2018b). Moreover, researchers have shown that higher-chroma colours presented in the computer-based context result in more intense, elicit and less relaxed states than in the non-computer-based context, as the intense projected light tires the cones (Golding and White, 1997). This suggests that the higher-chroma colours presented via VR headsets might be even more intense than those in the non-computer context. The only study on the impulsive effects of chroma is by Duan et al. (2018b) and investigated the effects of chroma on impulsiveness and arousal. They carried out psychophysical experiments and used response time and error rate as effective indicators. Their results show that chroma has a significant influence on participants' response times and error rates and influences impulsiveness and arousal.

Some researchers have reported evidence regarding the effects of different levels of brightness on people's emotions and cognitive behaviour. For example, Amhorst and Reed (1986) investigated these effects on males that rated female job applicants' dark versus light clothing and facial expressions. The findings showed that the men rated models who wore dark jackets more powerful and competent than those who wore light jackets. Furthermore, Frank et al. (2008) investigated the effects of black and non-black uniforms on professional football and hockey teams regarding aggressive behaviour. Other studies demonstrate that colours in different levels of brightness can cause significantly stronger effects on arousal and impulsiveness measured via SCRs and subjective emotions (Valdez & Mehrabiana, 1994; Wilms and Oberfeld, 2018a). Although the studies reviewed above are not directly related to a sense of presence and immersion, important indicators were highlighted, including 'arousal', 'impulsiveness', 'emotion' and 'aggressive behaviours'. As arousal is one of the effects of presence, it is reasonable to proposed assumption that adequate chroma levels and brightness of colours could potentially trigger people's level of presence in an immersive VR system.

Three kinds of methods are generally used to measure arousal and impulsiveness: self-reporting methods (i.e., verbal and non-verbal scales) (Eysenck and Eysenck, 1978; Patton et al., 1995), neuropsychological cognitive measures (i.e., IQ tests and paper-folding) (Kagan et al., 1964) and psychophysiological measures (i.e., EEG and ECG) (Lezak, 1995). More specifically, self-reporting methods are short and easy to manage. However, the methods may require good level of reading, the results from self-reporting methods depend on subjects' honesty and awareness of his or her behaviour patterns. Psychophysical measures are simple and easy to manage and are widely used in studies of arousal and impulsivity (Kagan et al., 1964; Bachorowski and Newman, 1985). Response time (tracing time) and error rate are generally the two main parameters measured to evaluate people's performance and behaviours. However, a study by Lezak in 1995 suggested that the measure is weak to repeat owing to the long-term learning and memory. Psychophysiological measures including electroencephalography (EEG), heart rate, and functional magnetic resonance imaging or functional MRI (fMRI) are the most commonly physiology techniques used when investigating the neurological processes behind arousal and impulsivity (Lohani et al., 2019). Moreover, accuracy in detecting cognitive workload has been found to significantly improved when physiological measures were conducted (Lenneman and Backs, 2009; Solovey et al., 2014 cited in Lohani et al., 2019). This research exploits neuropsychological cognitive measures. Two experimental studies were carried out to study the potential of colour stimuli on people's cognitive performance via immersive VR equipment. The association between response time and error rate generally refers to indicators for the neuropsychological cognitive measures (Duan et al., 2018a, 2018b; Husain et al., 2002) that were adopted in the analysis of the results obtained from the experiments.

2. Experiments

To address the research questions, we engaged in laboratory experiments to investigate the relationship between colour (chroma, brightness) and people's responses and assess whether there are differences in the influence of colour stimuli but that focus on using a neuropsychological cognitive measure method to evaluate people's arousal and impulsiveness in immersive VR environments.

2.1. Experiment 1: chroma

2.1.1. Participants

A total of twenty-eight participants (14 males and 14 females, aged between 20 and 28 years old) were recruited for the experiments. To avoid variable cultural effects and the possibility that some participants might be more logical in their approach, all participants are Chinese undergraduate and postgraduate students randomly selected from the School of Media, Harbin Normal University.

This study was approved by the University of Leeds Ethics Committee (ethics reference: LTSESN-134). After a careful study of the experiment description, all participants provided written informed consent prior to the experiment. All participants had the right to withdraw at any time without any reason. Participants' data and personal identities have been kept anonymous (see Table 1).

2.1.2. Colour conditions

The chroma experiments used green-coloured backgrounds in seven chroma levels (90%, 75%, 60%, 45%, 30%, 15% and 0%) with the equal luminosity settings. The green colour used in the hue experiments is defined as the 90% chroma in this study. The characteristics of the background colours in the VR headset are reported in Table 2.

2.1.3. Psychometric tests

Psychometric testing methods were applied to validate participants' cognitive performance as they are easily quantifiable and can feasibly be performed in both real-world and VR environments. The experiments employed six types of psychometric test to measure participants' logical thinking ability (logic rule and mathematics sequence tests), lateral thinking ability (spatial structure and rotation tests) and attention to detail (odd one out and same detail tests) (Table 3). The colours of the backgrounds and the orders of presentation of the questions were randomised (for each participant). Each participant was tested with each colour condition. Note, however, that for each participants the coloured backgrounds assigned to the questions within a test were also randomised. The purpose of this was to ensure that if one of the questions was perceived to be slightly more difficult than another, different backgrounds would remove any potential for bias (see Table 4).

Response time and error rate were the two main parameters measured during the experiments. The results of these tests were used to estimate the levels of arousal and impulsiveness shown by each participant, which can be used as an indirect way to understand how colour affects cognitive ability.

2.1.4. Experimental procedure

The experiments were conducted in a dark room with separate participants. All participants were required to complete the Ishihara colour vision test before entering the room to confirm that none had abnormal colour recognition ability. After passing the test, the instructions for the entire experimental procedure were given to each participant, followed by a sample task including each type of psychometric test to familiarise participants with the process before beginning the main experiment. Participants were asked to focus on the reference white background picture delivered by HMD VR Headset for 5 min to adapt the experiment. The main experiment started 5 min after they had adapted to the experimental conditions. Each participant was seated at a fixed distance of around 70 cm from a monitor in the VR environment.

Table 1
Demographic data of participants.

	Number	Percentage
Gender		
Male	14	50%
Female	14	50%
Age		
20–24	24	85%
25–30	4	15%
Education		
College/BA	24	85%
Master/PhD	4	15%

2.1.5. Results

Twenty-Eight participants took part in the experiment. Statistical analysis was performed using Statistical Product and Service Solutions software. Participants' impulsiveness and arousal were defined as: high arousal (HA), faster reactions and lower error rate; low arousal (LA), slower reactions and higher error rate; high impulsiveness (HI), shorter response time and higher error rate; and low impulsiveness (LI), longer response time and less error rate (all compared with the mean of the reference white colour background).

2.1.1.1. Data analysis – general trend. A statistical analysis was performed using Statistical Product and Service Solutions (SPSS, Armonk, NY, USA) software. Fig. 1(A) and (B) show the mean scores for response times and error rates, pooled over all six types of tests. The Kruskal-Wallis Test was used to determine the statistical significance of different levels of chroma backgrounding. Participants' impulsiveness and arousal (all compared with the mean) can be defined as High Arousal (HA), with faster reactions and lower error rates; Low Arousal (LA), with slower reactions and higher error rates; High Impulsiveness (HI), with shorter response times and higher error rates; and Low Impulsiveness (LI), with longer response times and lower error rates.

Fig. 1(C) visualises the chroma impacts on general performance in the Error–Speed space. The 30% chroma level is where participants performed the best (were the most aroused), with relatively shorter response times and the lowest error rates. People's responses to the 15% chroma were also located in the HA quadrant, suggesting that people experienced a relatively HA state with the 15% chroma backgrounds. Compared with the 0% chroma background results, people experienced the LA state with the 90%, 60%, 45% and 30% chroma backgrounds.

As for the response times, participants reacted fastest with the 30% chroma level backgrounds but reacted slowest with the 75% chroma level backgrounds. More specifically, significant differences were observed between the 75% and the 60% [$F(6, 1169) = 4.5$, ($p = 0.050$)], the 30% ($p = 0.01$) the 15% ($p = 0.003$) and the 0% ($p = 0.005$) chroma backgrounds.

Regarding the error rates, participants with the 60% [$F(6, 1169) = 10.9$] chroma level backgrounds were shown to make significantly fewer errors compared with participants with the 90% chroma backgrounds ($p = 0.001$), the 75% chroma backgrounds ($p = 0.001$), the 45% chroma backgrounds ($p = 0.001$), the 30% chroma backgrounds ($p = 0.001$), the 15% chroma backgrounds ($p = 0.001$) and the 0% chroma backgrounds ($p = 0.001$).

Fig. 2(A)–(C) summarise the chroma influence on arousal and impulsiveness according to gender. At 90%, 75%, 60% and 45% chroma, male participants made more errors and responded more slowly than female participants. At 30%, 15% and 0% chroma, male participants made fewer errors, and their response times were relatively faster than those of female participants. Looking at error rates and response times together, it seems that different chroma backgrounds have various effects on male and female participants. However, the only significant difference according to gender is observed in the error rates at the 60% chroma backgrounds [$F(1, 166) = 4.8$, ($p = 0.030$)], where male participants made significantly fewer errors than female participants.

Participants' logical thinking abilities were validated by the logical rule test and the mathematics sequence test. Generally, participants' logical thinking abilities, with respect to their error rates and response times, were significantly affected by different chroma backgrounds. As shown in Fig. 3(A) and (B), participants made significantly fewer errors with the 60% chroma backgrounds compared with the 90% [$F(6, 385) = 2.853$, ($p = 0.050$)], the 75% ($p = 0.003$), the 45% ($p = 0.032$), the

Table 2
The average characteristics of the background colours within the VR headset.

	R	G	B	L	a*	b*	C*	h (°)
Green_90%_chroma	23	229	171	81.38	−58.92	15.62	60.946	165.15°
Green_75%_chroma	57	229	181	82.00	−53.80	11.26	54.96	168.18°
Green_60%_chroma	92	229	190	83.00	−46.42	8.00	47.10	170.23°
Green_45%_chroma	126	229	200	84.30	−36.81	4.85	37.13	172.50°
Green_30%_chroma	161	229	210	86.12	−25.26	2.45	25.38	174.46°
Green_15%_chroma	195	229	220	88.36	−12.84	0.66	12.86	177.07°
Green_0%_chroma	229	229	229	90.94	−0.00	0.00	0.00	270.00°

Table 3
Functions of six types of psychrometric tests used in the experiments.

Cerebral hemisphere	Cognitive abilities	Tests
Right cerebral hemisphere	Logical abilities	Logical ability tests (Duan et al., 2018a, 2018b; Fletcher & Hattie, 2011) · Logical rule test · Mathematics sequence
Left cerebral hemisphere	Lateral thinking abilities (also known as spatial imagination abilities or lateral abilities in the study)	Spatial imagination ability tests (Duan et al., 2018a, 2018b; Fletcher & Hattie, 2011): · Spatial structure test · Rotation test
Right cerebral hemisphere: holistic perception. Left Right cerebral hemisphere: detail-oriented perception	Both the logical abilities and lateral thinking abilities (also known as detail abilities in this study)	Detail ability tests (Duan et al., 2018a, 2018b; Cairns & Cammock, 1978): · Odd one out · Same detail test

Table 4
Demographic data of participants.

	Number	Percentage
Gender		
Male	14	50%
Female	14	50%
Age		
20–24	24	85%
25–30	4	15%
Education		
College/BA	24	85%
Master/PhD	4	15%

15% ($p = 0.001$) and the 0% ($p = 0.003$) chroma backgrounds. With respect to the response times, significant differences were found between the 75% chroma and the 0% chroma backgrounds [F (6, 385) = 1.447, ($p = 0.005$)]. Together with error rates and response times (Fig. 3 (C)), participants performed best (were the most aroused) with 30% chroma backgrounds. Added to that, participants also experienced the HA state with the 90%, 45% and 15% backgrounds, but participants experienced the LI state with the 75% and 60% chroma backgrounds (Fig. 4).

The results of participants' performance in relation to lateral thinking abilities were validated by a spatial structure test and a rotation test. Participants' lateral thinking abilities were significantly affected by different chroma backgrounds in terms of error rates and response times. As for the error rates, participants made significantly fewer errors with the 60% chroma backgrounds [F (6, 385) = 5.852, ($p < 0.001$)] compared with the 90% ($p = 0.001$), the 75% ($p = 0.001$), the 45% ($p = 0.001$), the 30% ($p = 0.001$), the 15% ($p = 0.015$) and the 0% ($p = 0.001$) chroma backgrounds. Significant differences were also observed between the 15% and the 75% ($p = 0.015$), the 45% ($p = 0.027$) and the 30% ($p = 0.046$) chroma backgrounds. With regard to response times, participants responded fastest with the 30% chroma background and

Fig. 1. (A) General trend of response times by background colours in VR; (B) General trend of error rates by background colours in VR; (C) Colour impacts on overall performance visualised in the Error–Speed space in VR.

slowest with the 75% chroma backgrounds. Specifically, significant differences were found between the 75% [F (6, 385) = 4.360, ($p < 0.001$)] and the 90% ($p = 0.002$), 60% ($p = 0.001$), 45% ($p = 0.001$),

Fig. 2. (A) Gender differences in response times by background colours in VR; (B) Gender differences in error rates by background colours in VR; (C) Colour impacts on typical performance between male (M) and female (F) visualised in the Error–Speed space in VR.

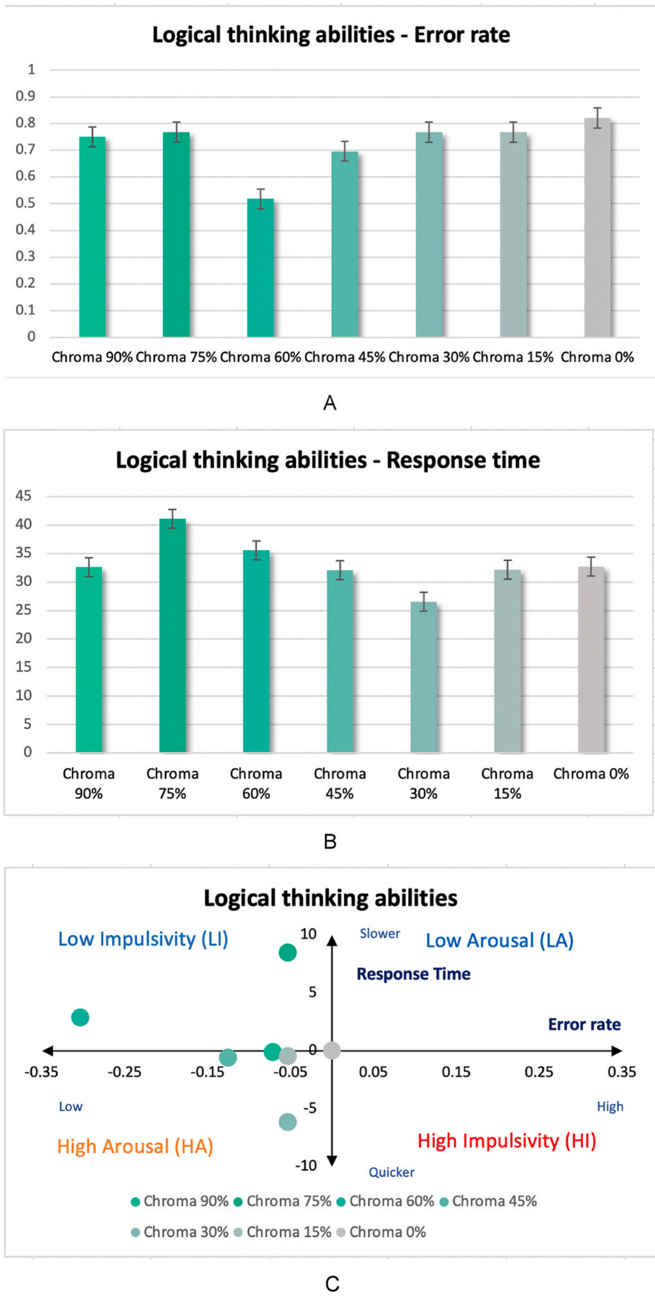

Fig. 3. (A) Response times of participants' performance in logical abilities by background colours in VR; (B) Error rates of participants' performance in logical abilities by background colours in VR; (C) Colour impacts on logical abilities in VR visualised in the Error–Speed space.

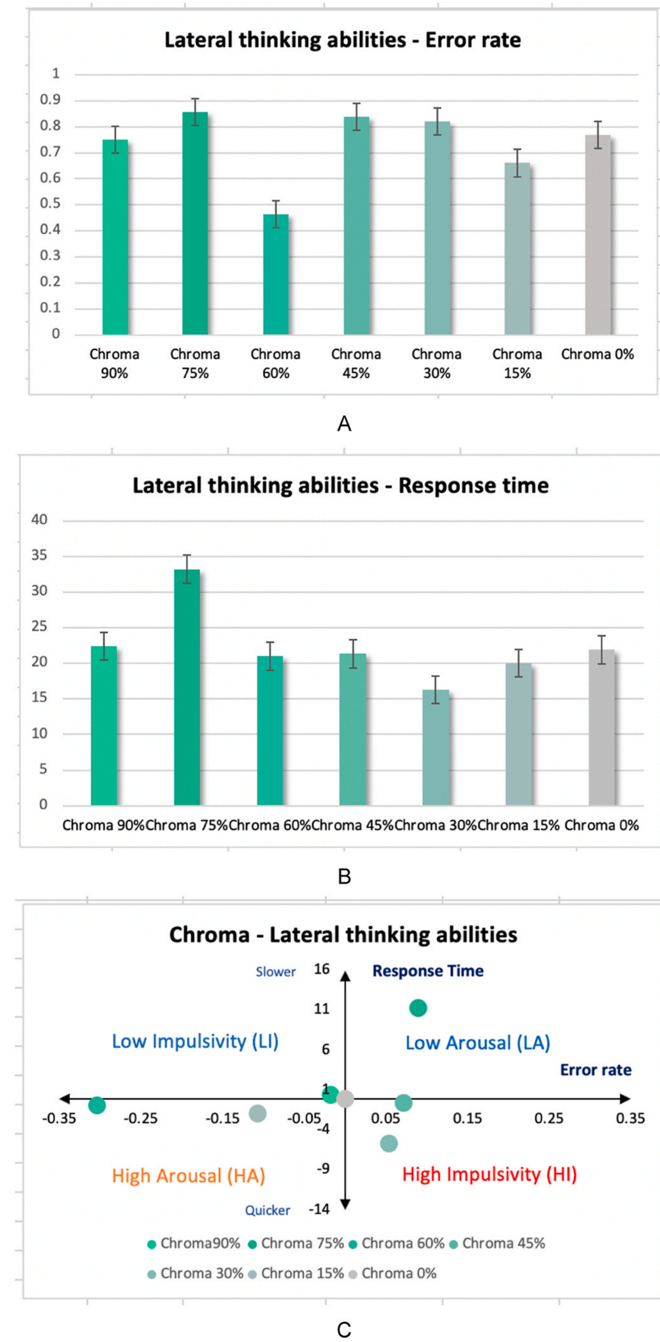

Fig. 4. (A) Response times in participants' performance in lateral abilities by background colours in VR; (B) Error rates in participants' performance in lateral abilities by background colours in VR; (C) Colour impacts on lateral abilities in VR visualised in the Error–Speed space.

30% ($p = 0.001$), 15% ($p = 0.001$) and 0% ($p = 0.001$) chroma backgrounds. Together with error rates and response times, participants' lateral thinking abilities were influenced by 60% and 15% chroma backgrounds with HA effects. Seventy-five per cent chroma backgrounds led to the LA state on participants' lateral thinking abilities. Forty-five per cent and 30% chroma were located in the HI quadrant, suggesting that participants experienced the HI state with 45% and 30% chroma backgrounds. Meanwhile, those with 90% chroma backgrounds resulted in an LA state.

People's attention to detail was measured by the odd-one-out and the same detail test. According to Fig. 5(A), participants made more errors with 90% chroma backgrounds and made the least errors with the 60% chroma backgrounds. As shown in Fig. 5(B), participants made the most errors with the 90% and the 0% chroma backgrounds and made fewer errors with the 60% chroma backgrounds. More specifically, significant differences were found between the 60% [F (6, 385) = 5.852, ($p < 0.001$)] and the 90% ($p = 0.001$), 75% ($p = 0.001$), 45% ($p = 0.001$), 30% ($p = 0.004$), 15% ($p = 0.001$) and 0% ($p = 0.001$) chroma backgrounds. When it comes to response times, participants responded fastest with the 0% chroma backgrounds and slowest with the 75% chroma backgrounds. Significant differences were found between the 75% [F (6, 385) = 4.360, ($p < 0.001$)] and the 60% ($p = 0.036$), 30% ($p = 0.022$), 15% ($p = 0.010$) and 0% ($p = 0.004$) chroma backgrounds. From Fig. 5(C), it can be seen that the colours at the 75%, 60%, 45%, 30% and 15% chroma levels are all plotted in the LI quadrant. Ninety per

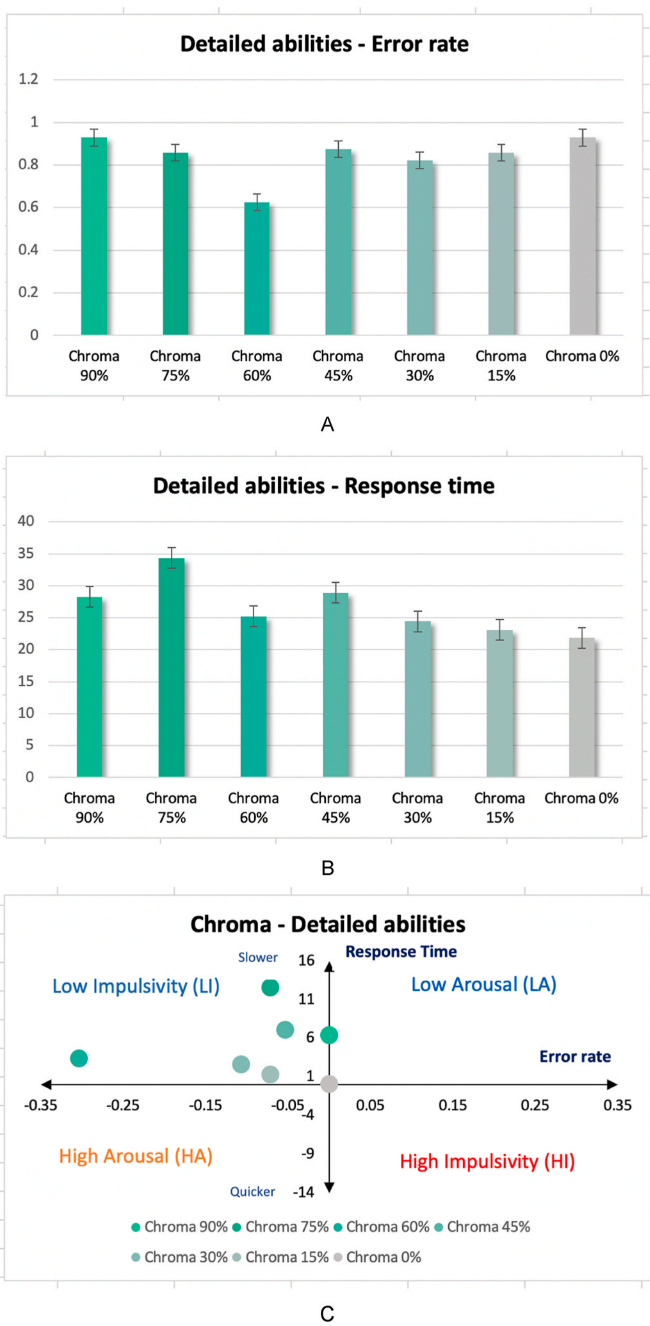

Fig. 5. Response times in participants' performance in detailed abilities by background colours in VR; (B) Error rates in participants' performance in detailed abilities by background colours in VR; (C) Colour impacts on detailed abilities in VR visualised in the Error–Speed space.

cent of the chroma level was located on the boundary of the LA and LI quadrants, meaning that 90% of the chroma levels of green influenced people to think relatively carefully about questions that require attention to detail.

2.1.6. Summary and discussion

The study evaluated the design potential of colour stimuli on people's cognitive performance, with a particular focus on testing various levels of chroma effects in an immersive VR environment. Results from psychological experiments showed that colours in different levels of chroma can significantly influence people's arousal and impulsiveness, suggesting that chroma has indirect impacts on emotions and cognitive performance in VR. Some key findings of this study can be summarised as follows:

- Generally, the 30% chroma level leads to the most aroused state. It induced participants to make relatively fewer errors with the shortest response times.
- Generally, the 60% chroma level leads to the lowest impulsive state. It induced participants to make the fewest errors with relatively slow response times.
- Statistical significance was found in cognitive performance between male and female participants at the 50% chroma level, where male participants made significantly fewer errors than female participants.
- People's logical thinking abilities were significantly influenced by different chroma backgrounds.
- The 30% chroma level led to the most aroused state in people's performance that requires logical thinking abilities. It induced participants to make fewer errors with the least response time when completing tasks that assess people's logical thinking abilities.
- The 75% and 60% chroma levels led to a relatively lower impulsive state. They induced participants to make fewer errors with slower response times when completing tasks that assess people's logical thinking abilities.
- People's lateral thinking abilities were significantly influenced by different chroma backgrounds.
- The 15% and 60% chroma levels led to a higher aroused state in people's performance that requires lateral thinking abilities. They induced participants to make fewer errors with slower response times when completing tasks that assess people's lateral thinking abilities.
- The 75% chroma level led to the lowest aroused state in people's performance that requires lateral thinking abilities. It induced participants to make the most errors with the slowest response times when completing tasks that assess people's lateral thinking abilities.
- The 30% chroma level led to the most impulsive state in people's performance that requires lateral thinking abilities. It induced participants to make the most errors with the shortest response times when completing tasks that assess people's lateral thinking abilities.
- People's attention to detail was significantly influenced by different chroma backgrounds.
- The 90% chroma levels of green influenced people to think relatively carefully about questions that require attention to detail.
- The 75%, 60%, 45%, 30% and 15% chroma levels led to a lower impulsive state for people's attention to detail.

Findings that the effects of chroma can significantly affect people's arousal and impulsiveness are associated with Duan et al. (2018c), who reported the chroma effects on people's performance by studying different levels of yellow, orange and red chroma colours. Moreover, Gorn et al. (2004) explored the effects of a web page's background colours while the page is downloading and found lower levels of chroma backgrounds were related to a decreased level of arousal state or a lower level of impulsiveness. It has been agreed and observed in this study that 30% chroma colours lead to the most aroused state, while the 60% chroma level leads to the lowest impulsive state. These findings support Gorn et al. (2004). However, they contrast with the findings from the study by Al-Ayash et al. (2016), which shows that vivid colours are more arousing than pale colours. In the experiment conducted by AL-Ayash et al., colours with low chroma had the effect of calming people. From the current chroma experiment, some results were seen to agree with those of Al-Ayash et al. (2016). Compared with 90% chroma levels of green, the 75%, 60%, 45%, 30% and 15% chroma levels led to a lower impulsive state for people's attention to detail.

Some novel findings from this experiment are that different levels of chroma significantly affect people's logical and lateral thinking abilities and their attention to detail in immersive VR environments. With regard to the design of VR environments, the findings of this research demonstrate the effective use of chroma to design VR environments to better trigger people's logical and lateral thinking abilities and attention to detail. More specifically, data obtained from the experiments showed that different chroma could significantly influence people's arousal and impulsiveness, suggesting that colour has an indirect impact on a person's presence and cognitive performance, in line with previous findings (Ilie et al., 2008; Zhang, 2019). However, this experiment is limited to a broad cultural and age group and needs to be conducted more comprehensively in the future. It is also difficult to use these selected samples to predict the trend of chroma effects on people's arousal and impulsiveness across the whole colour space.

2.3. Experiment 2: brightness

2.3.1. Participants

A total of twenty-eight participants (14 males and 14 females, aged between 20 and 28 years old) were recruited for the brightness experimental session. Considering the potential cultural impacts and the possibility that some participants might be more logical in their approach, all participants recruited in this experimental session were Chinese undergraduate students randomly selected from the School of Media at Harbin Normal University.

2.3.2. Colour conditions

The experiments used green-coloured backgrounds in four brightness levels (90%, 75%, 60% and 45%). The green colour used in the hue experiments is defined as 90% brightness in this study. The characteristics of the background colours in the VR headset are reported in Table 5.

In the brightness experiment, arousal and impulsiveness were also determined by response times and error rates. From Fig. 6(C), it can be seen that 75% brightness leads to an HA state for participants and has the shortest response times and the lowest error rates. The 45% brightness level is where participants experienced the LA state, with the longest response times and relatively higher error rates. The 60% and 90% levels of brightness stimulated participants with an HI state; in particular, the 60% level of brightness led to the highest impulsivity. To be specific (Fig. 6(A)), participants made the fewest errors with the 75% brightness backgrounds and had the highest error rates with the 90% brightness backgrounds. Significant differences were observed between the 75% [$F(3, 572) = 4.648$, ($p < 0.003$)] and the 90% ($p = 0.001$), 60% ($p = 0.008$) and 45% ($p = 0.008$) brightness backgrounds. Regarding the response times, Fig. 6(B) shows that participants responded slowest with the 45% brightness backgrounds and responded fastest with the 60% brightness backgrounds. Statistical significance was found between the 60% [$F(3, 572) = 1.703$, ($p = 0.165$)] and 45% brightness backgrounds ($p = 0.036$).

Fig. 7(A)–(C) summarise the brightness influence on arousal and impulsiveness in terms of gender. At 90% brightness, both male and female participants responded slower, with a relatively higher error rate, suggesting that both male and female participants experienced an LA state with 90% brightness backgrounds. Furthermore, at 75% brightness, male participants experienced an HI state, while female participants experienced an LI state. However, these trends are not statistically significant.

Participants' logical thinking abilities were measured by the logical rule test and the mathematics sequence test. According to Fig. 8(A)–(C), at 90% and 75% brightness, participants experienced an LA state, with a relatively higher error rate, and responded slower. Participants' logical thinking abilities performed best (highest arousal) at 45% brightness, with the lowest error rates and shortest response times. At 45%

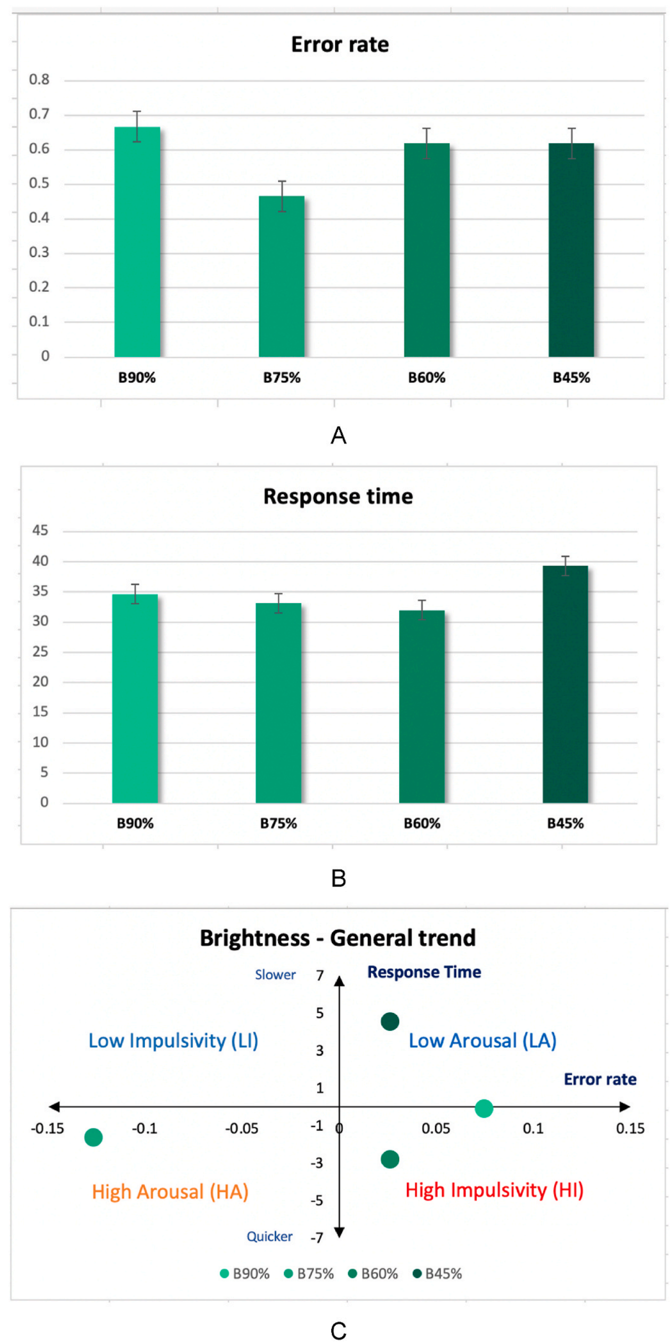

Fig. 6. (A) General trend of response times by background colours in VR; (B) General trend of error rates by background colours in VR; (C) Colour impacts on general performance visualised in the Error–Speed space in VR.

Table 5
The characteristics of the background colours in the VR headset.

	R	G	B	L	a*	b*	C*	h (°)
Green_90%_brightness	23	229	171	81.38	−58.92	15.62	60.95	165.15°
Green_75%_brightness	19	191	142	69.00	−51.34	13.69	53.13	165.07°
Green_60%_brightness	15	153	114	56.19	−43.22	11.15	44.64	165.53°
Green_45%_brightness	11	115	85	42.75	−34.93	9.04	36.08	165.49°

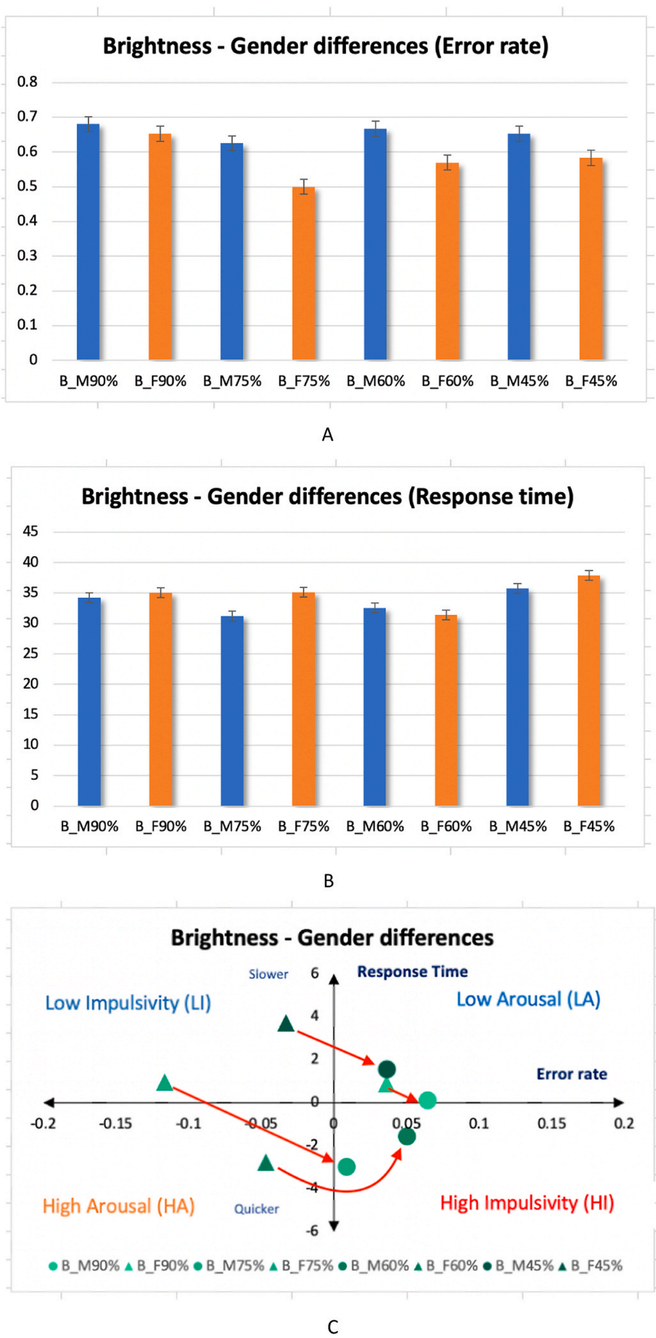

Fig. 7. (A) Gender differences in response times by background colours in VR; (B) Gender differences in error rates by background colours in VR; (C) Colour impacts between male and female participants visualised in the Error–Speed space in VR.

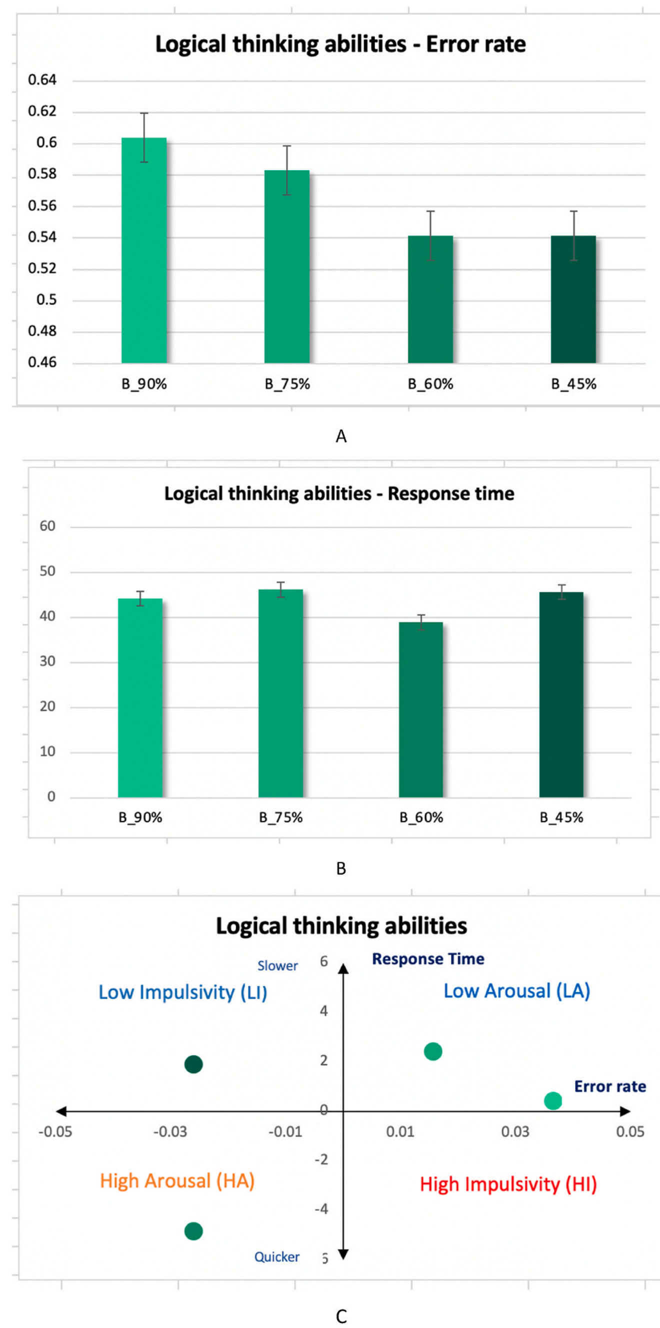

Fig. 8. (A) Response times in participants' performance in logical abilities by background colours in VR; (B) Error rates in participants' performance in logical abilities by background colours in VR; (C) Brightness impacts on logical abilities in VR visualised in the Error–Speed space.

brightness, participants' logical thinking abilities experienced the lowest impulsivity state. However, these trends are not statistically significant.

Participants' lateral thinking abilities were validated by the spatial structure test and the rotation test. Even though there is no statistical significance found in the data of error rates and response times (Fig. 9(A) and (B)), there is a tendency observed with respect to the influence of brightness on people's lateral thinking abilities in VR environments. Specifically, at 90% brightness, participants experienced the lowest arousal with the slowest response times and the highest error rates. Participants experienced the highest arousal with the 45% brightness backgrounds, with the shortest response times and the lowest error rates. Moreover, compared with the results in the 60% brightness backgrounds, participants experienced relatively lower arousal with the 75% brightness (Fig. 9(C)).

Participants' attention to detail was significantly affected by different levels of brightness. Specifically, in terms of the error rate (Fig. 10(A)), participants made significantly fewer errors with 75% brightness backgrounds [$F(3, 188) = 3.894$, ($p < 0.010$)] compared with 90% ($p = 0.012$), 60% ($p = 0.039$) and 45% ($p = 0.001$) brightness backgrounds. With respect to response times (Fig. 10(B)), participants responded significantly faster with 75% [$F(3, 188) = 2.558$, ($p = 0.057$)] than with 45% brightness backgrounds ($p = 0.007$). Together with error rates and response times (Fig. 10(C)), at the 90% and 45%

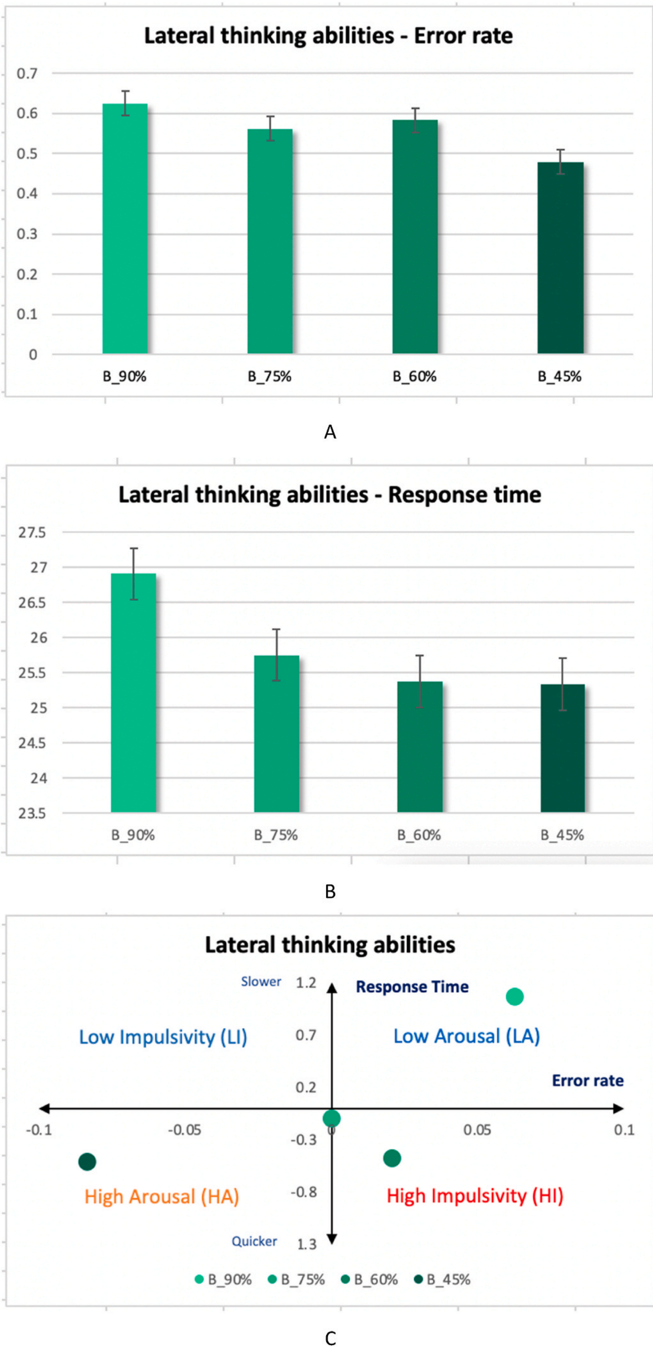

Fig. 9. (A) Response times in participants' performance in lateral abilities by background colours in VR; (B) Error rates in participants' performance in lateral abilities by background colours in VR; (C) Brightness impacts on lateral abilities in VR visualised in the Error–Speed space.

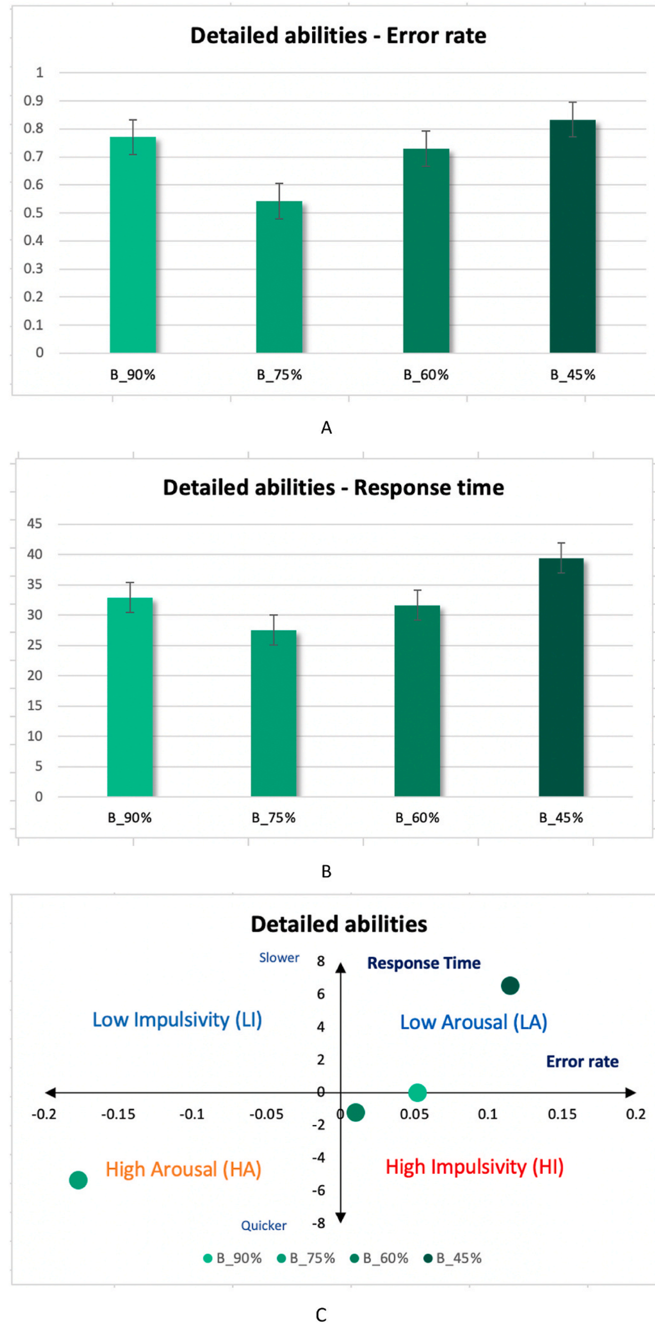

Fig. 10. (A) Response times in participants' performance in lateral abilities by background colours in VR; (B) Error rates in participants' performance in lateral abilities by background colours in VR; (C) Brightness impacts on lateral abilities in VR visualised in the Error–Speed space.

brightness levels, participants experienced a relatively lower arousal state. Seventy-five per cent brightness backgrounds stimulated participants with the highest arousal state, compared with the 45% brightness backgrounds, which led to the lowest arousal state.

2.3.3. *Summary and discussion*

It is recognised that the success of immersive VR experience design is due in part to its effective triggering of emotional engagement and cognitive performance. This experiment studied the effects of brightness levels on cognitive performance in an immersive VR space. The results of this experiment are important and demonstrate that brightness can significantly affect arousal and impulsiveness in an immersive VR environment. Findings can be summarised as follows:

- 75% brightness causes to the highest state of arousal. Participants made the least errors and responded fastest at this brightness level. More specifically, significant differences in error rates between 75% brightness and the 90%, 60% and 45% brightness backgrounds were found.
- 45% brightness results in the lowest state of arousal. It caused participants to make more errors and have the slowest response time.
- No gender differences were observed during the brightness experiment.

- Participants' attention to detail was significantly affected by different levels of brightness.

Early studies carried out in the real-world environments showed that even less immersive technologies, such as projectors, induced calming effects as white light seemed to reduce tension in the form of hand tremors (James & Domingos, 1953). Consistent with the work of Gorn et al. (1997), it was reported that the higher the brightness level was, the more relaxed people felt. This previous research suggests that higher brightness (i.e., lighter colours) should be more arousing than lower brightness (i.e., darker colours). In the current study, colour stimulations were delivered through an immersive VR headset. The results show that lower brightness did not seem to have a strong impact on people's cognitive performance. For example, brightness levels of 60% and 90% caused participants to experience a state of higher impulsivity. They made more errors and had shorter response times. A brightness level of 60% resulted in the highest impulsive state. However, other findings partially contrast with the those of previous research. 75% brightness led to the highest state of arousal, while 45% brightness led to the lowest. Regarding immersive VR experience design, it is reasonable to suggest that the level of brightness can significantly influence the sense of presence and immersion and positively induce emotional engagement and cognitive performance when navigating in immersive VR environments.

It was also indicated that well-designed levels of brightness in immersive VR environments can positively trigger people's intellectual abilities. These traits are important in the implementation of VR research and applications particularly for educational purposes. Specifically, significant findings came from the analysis of participants' logical and lateral thinking abilities and attention to detail. Statistical significance was found in the effects on people's attention to detail; participants exposed to 75% brightness made significantly fewer errors and responded faster than participants exposed to 60% and 45% brightness. This finding is agreement with that of Camgöz et al. (2004), who found higher brightness levels attracted the most attention.

3. Conclusions

This research explores the potential of colour as a design tool in the creation of well-designed immersive VR experience regarding ways to improve cognitive performance. A success of immersive VR experiences is that they can be designed to consistently induce emotional responses and engagement, which are important traits of VR applications and research on education, gaming, healthcare, and architecture. An interesting question arises from this research regarding the effective use of the key design tools, colour, in the creation of immersive VR environments. It is important to uncover how they can help to create a higher degree of emotional engagement and improve cognitive performance to have positive impacts on immersive VR experience design. Hypothetically, an immersive colour experience in VR could enhance people's performance of cognitive tasks compared to the standard colour imaging displays used in previous studies (Duan et al., 2018a, 2018b; Jacobs & Suess, 1975). This research conducted four studies that explored and compared the influence of selected colour stimuli in triggering people's emotional engagement and cognitive performance in both reality and immersive VR environments. The main aims of this research was to explore the potential of colour attributes (chroma and brightness) to optimise the design of immersive VR experiences to improve cognitive performance.

A previous study by authors sought to explore the design potential of the selective hues to improve cognitive performance in immersive VR environments (Xia, Henry, Li, Et Al., 2021). This study also investigated whether there are differences between the real-world and VR in terms of cognitive responses to selected hue. Experimental work carried out by Xia, Henry, Queiroz, & Westland (2021) found that a considered approach to immersive colour design can have a positive impact on emotional engagement even in a neural state (not engaged in any specific cognitive activity).

Based on the results obtained from Xia, Henry, Li, et al. (2021), the focus of the chroma and brightness studies was to explore the effects of other factors regarding colour (chroma and brightness) on cognitive performance in immersive VR environments. This study aimed to evaluate whether systematically changing one or two characteristics among the three features (hue, chroma, and brightness) of selected colours in the immersive VR environments would improve cognitive responses. Hence, this study focused only on measuring cognitive responses in the designed immersive VR environments. The chroma and brightness studies took advantage of the same cognitive neuropsychological measures as in the hue study. Considering the literature review and the results obtained from the hue study, green was chosen as the colour to explored in the chroma and brightness studies. The results showed that the effects of brightness can significantly affect level of arousal and impulsiveness in an immersive VR environment. Additional significant findings of this research came from an analysis of the logical and lateral thinking abilities of the participants and their attention to detail. Specifically, statistical significance was found for the effects on people's attention to detail; at 75% brightness, participants made significantly fewer errors and responded faster than those at 60% and 45% brightness, respectively.

In previous research, the effects of colour on emotional and cognitive performance have seldom been investigated in depth, especially regarding immersive VR environments. The results of this research are important contributions to knowledge in the area of colour psychology and VR design. Main contributions of this research provide an enhanced understanding of the influence of colour attributes (chroma and brightness) on people's cognitive performance in immersive VR environments.

The application of the knowledge uncovered in this research will provide help to VR developers in introducing and making effective use of advanced immersive computing technologies. The new knowledge uncovered by this research highlights that selective colour can improve intellectual abilities and immersive VR experience design. The implementation may lie in the creation of VR applications that are specifically designed to trigger users' creativity, imagination, logical thinking abilities, or attention to details. For example, the creative design process of immersive VR environments would draw on the use of colour and light design to trigger user engagement, cognitive performance, and intellectual abilities more effectively. This can promote designers to use VR as a means of design tool. Furthermore, this research can encourage various VR applications and research in education, as it demonstrates the effective use of colour to stimulate cognitive abilities (i.e., logical thinking abilities, lateral thinking abilities and attention to detail). This could guide VR developers and designers in constructing VR environments for educational purposes (i.e., applications for mathematics or other logical abilities training). Moreover, gender differences in cognitive performance can be considered by VR developers or designers as an influential factor in the creation of immersive VR experiences, for example, for educational and therapy-based aversion treatments purposes. Finally, the methodology used in this thesis could also offer a basis for future research.

During this research, many avenues for further research became apparent, and some likely future research directions were mentioned (i.e., creative design, marketing and business, and healthcare and education). Some of these future research directions are specifically related to the examination of the methods used here. More case studies must be conducted in order to explore a larger sample size in relation to colour stimuli on people's physiological responses delivered through VR in the preliminary study. Similarly, the reliability of the findings on hue, chroma, and brightness must be examined; further studies should be conducted to re-test the data on a group of participants from different cultural backgrounds to determine whether the similar conclusion would be made. The findings of this research have suggested that colour can affect people's arousal and impulsiveness in both reality and immersive VR environments. More work should be done to explore the relationships between the effects of colour combinations on emotional and cognitive performance in immersive VR technology. It would be interesting to compare such findings to this research.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chb.2023.107853.

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