ORIGINAL ARTICLE

Mitigating potential injuries in gymnastics: Human factors research approach on colour coding and visual perception in high-bar training

ZIHO KANG , CESAR E. GRACIA SALGADO, SARAH C. GATES

Industrial and Systems Engineering. University of Oklahoma. Oklahoma, United States of America.

ABSTRACT

If appropriate colour coding is applied, gymnasts' visual perception during landing may improve, potentially leading to reduced injuries and enhanced performance. An experiment and a survey were conducted with professional gymnasts at the University of Oklahoma. For the experiment, gymnasts' visual perceptions were assessed for different manoeuvres using distinctive colours: floral white, lime yellow, and deep blue. Subsequently, we conducted a survey to investigate their preferred colour(s), reasons behind their choices, and any previous injury experiences related to poor visibility. Significant differences between floral white and lime yellow for more complex manoeuvres (e.g., double layout flip with single twist, p = .01, and double layout flip with double twist, p = .03). Survey results indicate that floral white colour was not preferred since the gymnasts reported difficulty distinguishing the floor from the ceiling. Lime yellow was preferred due to its high contrast, and deep blue was similarly favoured because gymnasts were accustomed to it. Additionally, the gymnasts reported other potential colour(s) and/or patterns that could enhance visual perception. The study provides insights into the potential benefits of colour-coded landing areas and establishes a foundation for further research on utilizing other hue variations, lightness, chroma intensity, patterns, and related factors.

Keywords: Performance analysis, Sports health, Sports performance, High-bar training, Colour coding, Human factors, Visual perception.

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Corresponding author. *202 W. Boyd St, Room 124, School of Industrial and Systems Engineering, University of Oklahoma, Norman, Oklahoma, 73019 United States of America.*
E-mail: zihokang@ou.edu
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INTRODUCTION

One of the pioneering research projects, which is based on interviews with gymnasts, highlights their limited control over external factors such as mats, lighting, and equipment, and as a result, gymnasts are advised to anticipate and prepare to maximize their control over those external factors (Ravizza & Rotella, 1982). Specific to the mat standards, the International Federation of Gymnastics maintains updated specifications that outline dimensions and composition to prevent potential injuries (Fédération Internationale de Gymnastique, 2024), and previous research efforts have centred around improving the materials used in energy-absorbing mats (Sundholm, 2014; Tomin & Kmetty, 2022).

However, to the best of our knowledge, there are no specific standards or specifications format colour. The choice of mat colour is not a personal preference for gymnasts; rather, it is determined by equipment manufacturers or competition organizers. Therefore, mat colours may vary depending on the region. As an example, American Athletics Inc. is known to provide blue-coloured mats in the United States ("*Competition Landing Mats*," n.d.), while Gymnova offers white-coloured mats in Europe for certain official competitions ("*Gymnova*," n.d.). These two brands are used for specific meets based on the sponsor and location of the competition. Furthermore, many gyms may choose mat colours that align with their branding.

Despite any personal preferences gymnasts may have, the gymnasts often lack the opportunity to utilize their preferred mat colour. Certain colours may be easier for gymnasts to spot, potentially enhancing their perception during landings. Improved perception can contribute to safer landings and better overall performance. Interestingly, scientific evidence or experiments specifically examining the effect of mat colour in professional gymnastic events, such as the high-bar (also known as horizontal-bar), are scarce. However, the visibility of landing mats likely plays a crucial role in gymnasts' sense of self-security and may help reduce the risk of injuries.

In the context of gymnastics injuries, prior research indicates that the absence of a spotter—someone who observes and reacts to orient or position the athlete when they lose spatial awareness—accounts for a significant portion of injuries. Specifically, studies report that not having a spotter contributes to 85% (Lindner and Caine, 1990) of all gymnastics-related injuries. Among these injuries, knee and ankle injuries during twisting manoeuvres and other lower limb injuries are the most common types (Grapton et al., 2013; Greier, Drenowatz, & Mairoser, 2022; Katz, 2020; Williams et al., 2023). Consequently, emphasizing correct landing techniques and maintaining proper body posture is essential for preventing gymnastics injuries (Daly, Bass, & Finch, 2001).

Especially, visual perception might play a critical role in maintaining spatial awareness and preventing injuries in gymnastics. When gymnasts lack vision, their stability significantly decreases (Davlin, 2001). High-bar routines, in particular, require gymnasts to execute intricate movements before landing on the mat. Visual perception of the mat's location enables gymnasts to align their bodies for controlled landings, effectively absorbing impact forces and reducing injury risks. This heightened awareness allows precise execution of movements and optimal body control throughout the dismount phase. Gymnasts must perform manoeuvres while simultaneously preparing for a controlled landing on the mat (Takei et al., 1999). Therefore, athletes often maintain spatial awareness by looking down at the mat whenever possible. Existing research demonstrates that gymnasts observe the landing location during preparatory giant swings (Heinen, Velentzas, & Vinken, 2012).

Considering the importance of visual perception, appropriate colour coding could be implemented to enhance the visibility of landing mats. Humans naturally draw explicit attention to colour stimuli (Elliot and Maier, 2014). As an example, in long jump approach runs, using a yellow-coloured take-off board (complementary to the runway's blue track surface) instead of the traditional white board allowed athletes to initiate their regulation two strides earlier. This adjustment resulted in better pre-jump positioning due to increased visual perception (Theodorou et al., 2013). Similarly, in another study, athletes wearing coloured lenses demonstrated significantly shorter hand-eye coordination times with light-yellow and dark-yellow lenses compared to dark-grey lenses (Kohmura, Murakami, & Aoki, 2013).

In the field of Human Factors research, two critical colour principles enhance visual perception: conspicuity and visibility. These principles play a crucial role in clearly identifying the location of objects, such as gymnastics mats, under various viewing conditions. High conspicuity and visibility are achieved through the use of prominent colours or strong contrasts, and existing research shows that humans exhibit high sensitivity to lime yellow colour (Federal Emergency Management Agency, 2009; Proctor and Zandt, 2018; Solomon & King, 1995).

In this research, we investigated high-bar gymnasts' visual perception levels and colour preferences from several aspects. First an experiment was conducted with the professional gymnasts who conducted simple to complex manoeuvres. During the experiment, we evaluated the gymnasts' visual perception levels of the coloured mats using a Likert-scale question. After, we conducted a survey to assess their colour preferences, reasons for choosing such colour(s), previous injury experiences, among others. Details are provided in the following section.

MATERIAL AND METHODS

Participants

Nine professional gymnasts, having an average age of 20.2 (*S.D.* = 1.1), were recruited from the University of Oklahoma (OU) Men's Gymnastics Team. The participants had an average of 14.6 years of experience (*S.D.* = 2.6) and were active professional gymnasts.

Measures

Regarding the experiment (i.e. gymnasts performing manoeuvres), the visual perception level of the mat (i.e. the ability of a gymnast to see the mat between the time when they release their hands from the high bar until they land on the mat) was measured. In detail, gymnasts were asked to provide a Likert-scale value between 0 (no visibility: didn't see at all) and 10 (perfect visibility: perfectly visible throughout the manoeuvre) immediately after each manoeuvre for each mat colour. Mor details of the manoeuvres and mat colours are explained in the *Procedures* section below.

After the experiment ended, a survey was administered. The survey questions included: (1) preferences (i.e., positive, neutral, negative) on using a certain mat colour (e.g., floral white, lime yellow, deep blue), (2) the reason for choosing such a preference for each colour, (3) which mat colours they have used during their professional career, (4) whether they had any injuries because they were not able to see the floor or mat, (5) a detailed reason for why the injury occurred, (6) any colour, colours, colour combinations, and/or patterns they would choose if they had a choice, and (7) the reason behind their choices for colour, colours, colour combinations, and/or patterns.

Procedures

The experiment was approved by the Institutional Review Board (#15861) and the gymnastics Head Coach at OU. The second author, who is a professional gymnast at OU, recorded the data. Three types of mat colours along with the corresponding colour codes (i.e. floral white (Hex #FFFAF1, RGB (255, 250, 241)), golden poppy yellow (Hex #FFC500, RGB (255, 197, 0)), and deep blue (Hex #434A75, RGB (67, 74, 117)) are provided in Figure 1. Note that golden poppy yellow can create a strong contrast that might accentuate the visual impact, therefore, we chose this colour as a proxy for the lime-yellow colour for this experiment. Deep blue is the same colour used for training at OU.

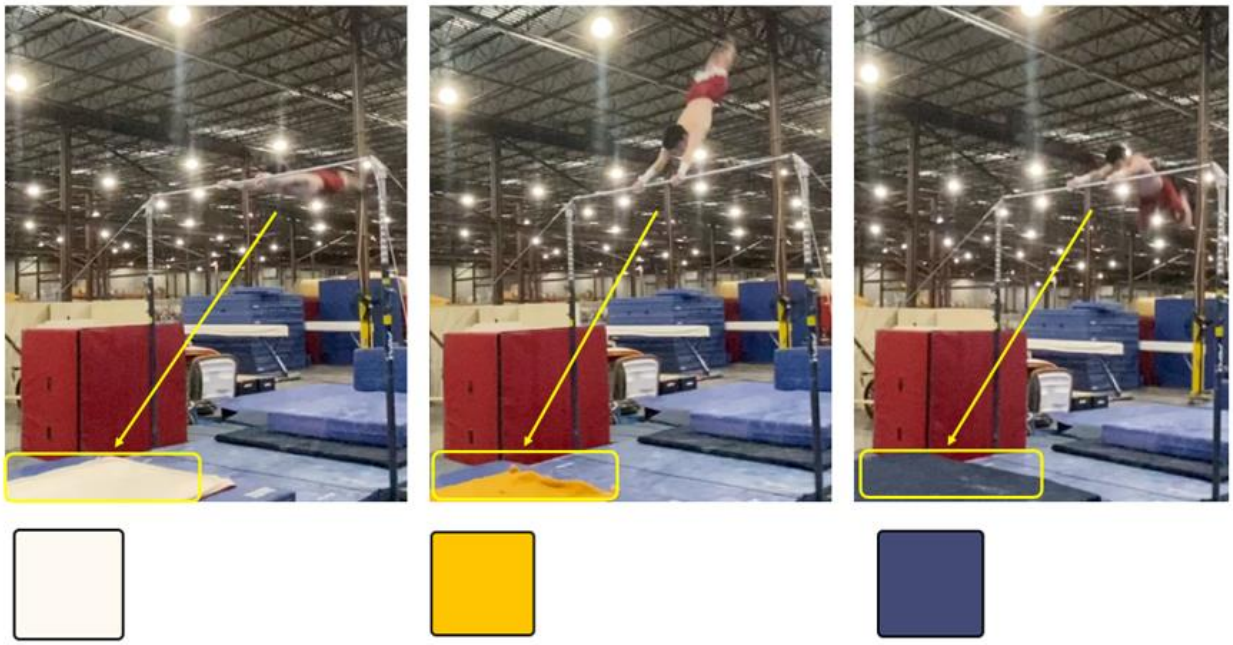

Figure 1. Experiment environment and mat colours used.

The manoeuvres included gymnasts executing three tasks in random order: single layout flip (SF), double layout flip with a single twist (DFST), and double layout flip with a double twist (DFDT). The gymnasts performed these each manoeuvre using three mat colours: floral white, lime yellow, and deep blue. The sequence of providing different mat colours was also randomly ordered. After each manoeuvre, the gymnasts provided their visual perception level by assigning a Likert-scale value. Professional gymnasts participated in the survey after executing the manoeuvres. Unfortunately, data for the deep blue colour mat were not saved for the DFDT manoeuvre due to an unexpected issue, and it was not feasible to schedule another time. Therefore, the analysis of the SF and DFST manoeuvres was possible for the floral white, lime yellow, and deep blue colours, while the analysis of the DFDT manoeuvre was possible for floral white and lime yellow colours.

Analysis

First, recorded videos were observed to obtain sample snapshots that better illustrate when the mat is observed during the manoeuvres. Next, descriptive statistics (i.e. means and standard errors) of the reported visual perception levels were plotted to identify any trends or differences. Since the data were not normally distributed, non-parametric statistical tests were used. Specifically, for the SF and DFST manoeuvres, Kruskal-Wallis tests were applied, followed by post-hoc pairwise comparisons using α-adjusted Wilcoxon

tests to consider the familywise error rate. For the DFDT manoeuvre, a Wilcoxon test was applied since only two levels, floral white and lime yellow, were compared. Additionally, nonparametric bootstrapping was conducted to gain additional insights for future research. Finally, self-report analysis was used to tally and summarize the answers to all the questions listed in the Measures section above.

RESULTS

Experiment results

Examples of the gaze behaviours of the gymnasts are provided in Figure 2. In Figure 2, we can observe that the gymnasts can spend most of their time seeking and looking down at the mat during the SF and DFST manoeuvres, whereas the gymnasts lose contact with the mat for a longer duration for the DFDT manoeuvre. Note that the SF and DFST experiments were conducted during the evening, whereas the DFDT experiment took place during the daytime at a different location; however, despite these variations, no confounding effects exist, as the visibility level evaluations were assessed and compared for each independent manoeuvre.

Figure 2a. Examples of eye gaze directions during manoeuvres. Single layout flip (SF).

Figure 2b. Examples of eye gaze directions during manoeuvres. Double layout flip with single twist (DFST).

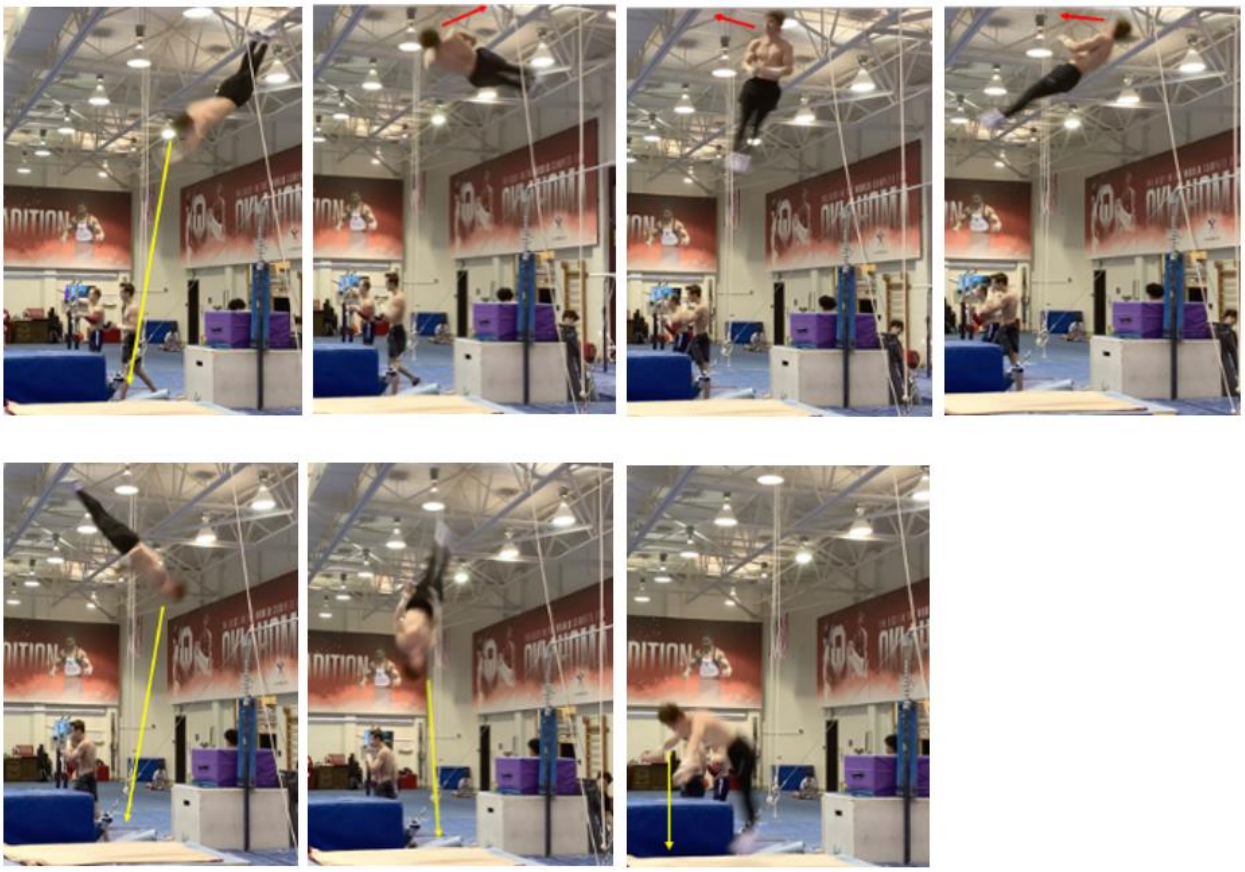

Figure 2c. Examples of eye gaze directions during manoeuvres. Double layout flip with double twist (DFDT).

The descriptive statistics (i.e. Means and Standard Errors) of the participants' visual perception levels are plotted in Figure 3. In Figure 3, we can see trends that yellow-coloured mat was easier to spot than the white-coloured mat as the task difficulty increased.

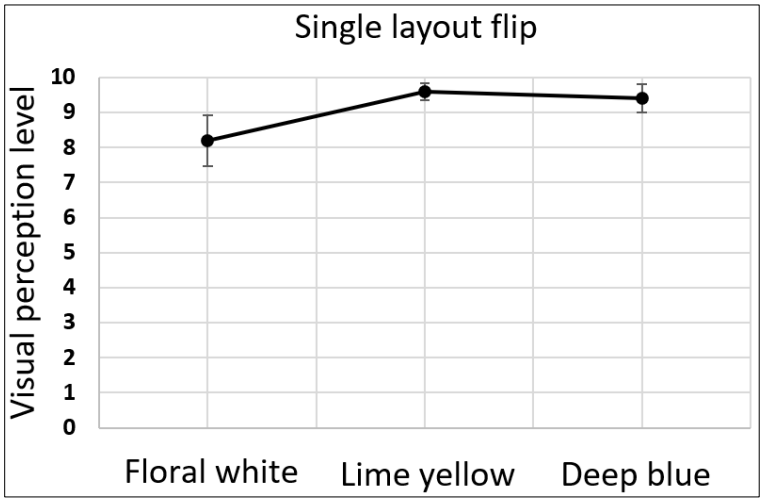

Figure 3a. Visual perception levels (Likert scale values) on each colour during each manoeuvre. Single layout flip (SF).

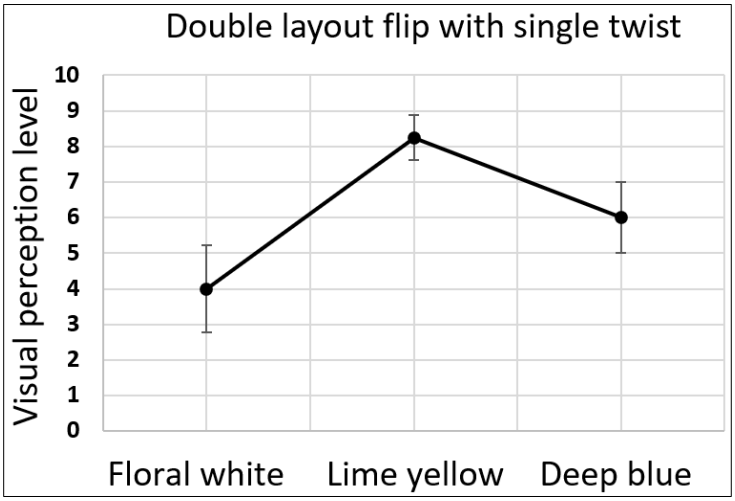

Figure 3b. Visual perception levels (Likert scale values) on each colour during each manoeuvre. Double layout flip with single twist (DFST).

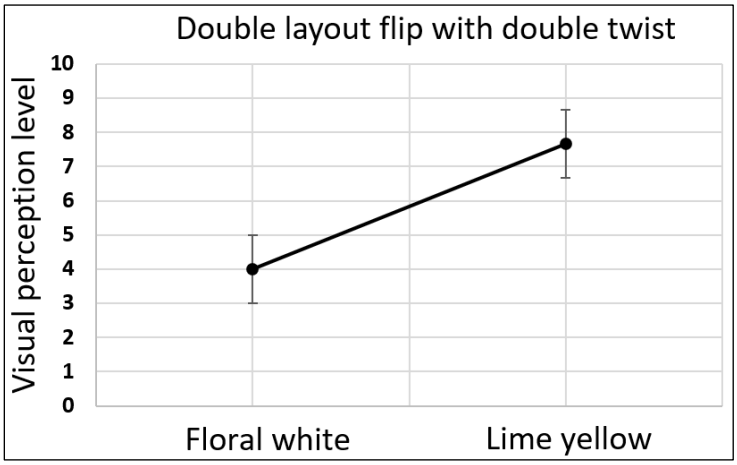

Figure 3c. Visual perception levels (Likert scale values) on each colour during each manoeuvre. Double layout flip with double twist (DFDT).

Table 1. Bootstrapping (1,000 repetitions): CI indicates confidence interval. Results are rounded to 1 decimal place.

Task	Task	Colour	Mean	95% CI
Visual perception (Likert scale)	Single layout flip (SF)	Floral white	8.2	[7.0, 9.5]
		Lime yellow	9.6	[9.2, 9.5]
		Deep blue	9.4	[8.7, 10.0]
	Double layout flip with single twist (DFST)	Floral white	4.0	[2.5, 5.5]
		Lime yellow	8.3	[7.6, 9.2]
		Deep blue	6.0	[4.8, 7.3]
	Double layout flip with double twist (DFDT)	Floral white	3.9	[2.9, 5.1]
		Lime yellow	7.7	[6.5, 8.8]

For the manoeuvres single layout flip (SF) and double layout flip with a single twist (DFST), Kruskal–Wallis tests on colours revealed significant differences in the gymnasts' visual perceptions (H = 9.48, *p* = .01). Post

hoc analyses (i.e., multiple comparisons) were performed using Wilcoxon tests with $\alpha = 0.017$ (or 0.05/3). The results showed that white vs. yellow were significantly different (W = 6.52, $p = .01$) for the DFST manoeuvre, but other pairs (i.e., yellow vs. blue, and white vs. blue) were not significantly different. Regarding the manoeuvre double layout flip with a double twist (DFDT), the Wilcoxon test with $\alpha = 0.05$ indicated that a significant difference existed between white and yellow (W = 4.96, $p = .03$). Bootstrapping results for both visual perception and mat gaze duration are provided in Table 1.

Self-report analysis results

Self-report analysis on the gymnasts' preferences after participating in the experiment is provided in Table 2. Most participants preferred the lime yellow or the deep blue mats, while the majority did not prefer the floral white mat. The critical reason for not preferring the floral white mat was the difficulty in clearly distinguishing the ceiling (which has white lights) from the floor. In addition, the reasons for their preference for the lime yellow or deep blue were distinctly different. Lime yellow was preferred because it provided high contrast, making it easy to locate the floor, whereas deep blue was preferred because it doesn't stand out too much but still provides enough contrast to distinguish the ceiling and floor. More importantly, deep blue was the colour to which they were accustomed.

Table 2. Self-report analysis of the gymnasts' preferences for the tested three colours.

Colour	Classification (count)	Representative or notable quotes
Floral white	Positive (1)	"The contrast between the blue surroundings in the gym (during training) and the white landing mat helped me spot the mat easier. However, if the surroundings are floral white, it would be difficult to distinguish it from the white ceiling and walls, which I would not have liked."
	Undecided (1)	"I didn't feel noticeable impact on ground visibility."
	Negative (7)	"Floral white mat blends with ceiling due to the colour and glare of the lights." "Confusing, feels like staring at the ceiling instead of the ground." "Brightness is excessive and merges with the ceiling lights which are white." "Hard to judge distance since the colour is too bright."
Lime yellow	Positive (7)	"The (lime yellow) colour made it easier to tell the difference between the floor and ceiling, and the brightness of the colour made it easier to see." "Lime yellow was easier to spot because it was brighter than the surrounding colours." "Easier to judge distances." "Lime yellow is a very vivid colour, and it isn't a distraction nor is hard to find." "Because of the bright nature of lime yellow, I was able to see the mat decently well when moving fast and preparing for the landing."
	Undecided (1)	"It was not too distracting; however, I'm not too used to the colour lime yellow when it comes to landing mats."
	Negative (1)	"I am able to see the mat better, but it stands out too much."
Deep blue	Positive (8)	"It's what I am used to. It does not blend into the ceiling and doesn't stand out too much." "I used deep blue since I started gymnastics, so that's what I'm used to seeing." "I'm used to using deep blue, and the contrast between the celling and floor is good." "I like deep blue since it is mainly the colour I land on. Although the colour isn't vibrant and as easy to spot as the others, I can still see my landing. I feel as though partially because I mostly use this colour (blue) for a landing mat. It's most natural to me. Because the colour isn't vibrant, I am able to not feel rushed nor excited when I prepare for landing." "It just seems normal."
	Negative (1)	"The mat colour is similar as the floor around it, so it is difficult to judge the correct distance."

Regarding which colour mats were used by the participants, various answers were obtained. The colours and the number of responses provided by the participants are as follows: white (3), yellow (2), blue (9), dark

blue (1), teal (2), red (7), green (1), grey (1), orange (1), and black (2). The question of whether the participants had any injuries because they were not able to see the floor or mat resulted in the following responses: Four participants answered "*yes*," while five participants answered "*no*." For those who responded "*yes*," the reasons provided were as follows:

> "*I was not able to see the floor and opened up too late to prepare for the landing."*
> *"I didn't absorb the landing correctly because I got confused by the ceiling lights."*
> *"I didn't see the mat and over-rotated, so I landed on my back."*
> *"The grey-coloured mat was always hard to see, and I would either think that I saw it and open out too early or didn't see the mat at all and opened too late*."

Finally, we provided an option for the participants to choose whichever colour, combination of colours, and/or layout of colours, and the results are provided in Table 3.

Table 3. Self-report analysis of the gymnasts' preferences for any colour, colours, colour combinations, and/or patterns.

Colour or colours	**Classification (count)**	**Reason of choosing the colour or colours**
Single colour	White (0)	n/a.
	Yellow (2)	"I feel like there are other combinations that would be a lot better but yellow has been the only one I tried, and I like it so far." "I really liked that colour during the experiment. however, this made me think a lot and I feel like other combinations with forms might help too but I would have to try it."
	Yellow or orange (1)	"Darker colours are usually hard to find and white and cream is a reflection of the ceiling. Yellow and orange makes it easy to see the ground while preparing for any landing."
	Blue (2)	"Blue is the easiest on the eye in my opinion, but I've always used this colour so it makes sense that it is the most familiar." "It's what I'm used to."
	Blue or red (1)	"Blue and red are vastly different colours from the ceiling lights. Interestingly enough, I think even tan could work."
Combination of colours	Striped yellow and red (1)	"It would really stand out against the ceiling and other colours in the mix of things."
	Striped blue and red (1)	"They give you a mixture of colour recognition in order to better recognize distance to the ground and where you are going to land."
	Tic-tac-toe pattern (1)	"A tic-tac-toe pattern, red on the corners, yellow one the middle borders, and green in the middle. This pattern will allow me the figure where I am in the air and how I need to adjust before landing. If I'm going to land short or if I need to pull less to slow the rotation down. I could also see if I need to get ready if I'm too much to the left or right side with the corners." 

DISCUSSION

The comparisons of visual perception levels provided a clear insight into how mat colour significantly affects gymnasts' ability to see the floor or mat. The vivid colour, lime yellow, which provides high contrast, stands out as particularly effective. Interestingly, the visual perception levels for lime yellow and deep blue were not significantly different. The results of the visual perception levels align with the survey responses. The majority of gymnasts mentioned that they were unable to distinguish the ceiling from the floor when the floral white

mat was used. Although the gymnasts showed similar preferences for lime yellow and deep blue, but their reasons differed. Those who preferred yellow emphasized its vivid colour, making it easier to spot. In contrast, those who preferred blue cited comfort, as it was the colour they had been using since childhood. However, both colours (blue and yellow) were acceptable because they allowed differentiation between the ceiling and floor. The effect of the mat colour can be crucial for difficult manoeuvres like the double layout flip with a double twist, during which gymnasts lose eye contact with the mat or floor for longer periods of time. While the results suggest that lime yellow might be a viable alternative to floral white, it's essential to consider various aspects of colour. These include lightness and chroma intensity, which were not specifically investigated in this research. While this study focused on varying colour hue, future research could explore the impact of other factors listed above.

When examining the survey results, it becomes evident that gymnasts had the opportunity to use various mat colours, even if they primarily trained on blue mats. Their exposure to different mat colours, combined with the use of yellow mats during this experiment, seems to have piqued their interest in exploring alternative colour options or combinations. In more detail, when asked to choose any colour (or colours) if given the chance, approximately one-third of the gymnasts preferred yellow, another one-third favoured blue, and the remaining one-third opted for a combination represented as strips or a tic-tac-toe pattern. This tic-tac-toe pattern resembles the "*double mini*" pattern (with blue on the boundary, yellow in the middle, and red in the centre) used in some competitions. Using such a pattern might improve their ability to adjust their landings, potentially reducing the risk of injuries.

Regarding the survey responses on injuries, some participants reported that injuries occurred due to poor visibility of the mat. Although we couldn't verify the exact mat colour used during each injury, one gymnast mentioned an injury while using a grey mat, while another expressed difficulty distinguishing the ceiling from the floor. These survey results highlight that the white mat might not be an optimal solution, especially considering that ceiling lights are typically white. Note that, if changing the mat colour proves challenging, it might be worthwhile to explore the possibility of gymnasts using coloured lenses. Research conducted in other athletic environments has utilized coloured lenses to investigate the effects of colour changes on manoeuvres (Kohmura, Murakami, & Aoki, 2013).

We did attempt to calculate mat gaze durations during high-bar manoeuvres by observing recorded videos, but the results are not included in this paper as we encountered many challenges. The quality of still images captured from the videos was lower than expected, and determining the duration was highly subjective, relying on analysts' judgments. However, there's a promising avenue for better quantifying mat gaze duration using eye tracking glasses (Hüttermann, Noël, & Memmert, 2018; Aksum et al., 2020). Eye tracking research specific to high-bar activities has been limited (Heinen, Velentzas, & Vinken, 2012). Fortunately, recent advancements in eye tracking technology might offer the potential to enhance our analysis of gymnasts' visual perception. If eye tracking technology can be accurately applied, it could revolutionize our understanding of the gymnasts gave behaviours. Beyond eye fixations or durations, we could explore characteristics of visual scan paths using algorithms developed in other research areas, such as visual entropy (Jeong, Kang, & Liu, 2019), visual grouping (Kang & Landry, 2015), dynamic visual scanning networks (Mandal & Kang, 2018), among others.

Finally, the research results were based on professional gymnasts in the United States. To draw more generalized conclusions, additional participants are needed, including gymnasts from other regions, female gymnasts, and different age groups. Nevertheless, our research provides a foundation and may spark wider interest among stakeholders to explore the possibility of using colours to enhance visibility.

CONCLUSIONS

We hypothesized that using a lime-yellow mat colour could potentially enhance the visual perception of professional gymnasts and contribute to their spatial awareness, specifically in terms of knowing the location of the floor (i.e. mat). The lime yellow or deep blue mats were significantly more visible compared to the floral white mat, and the biggest issue with using a floral white mat was that the ceiling and floor were difficult to distinguish. Losing spatial awareness can lead to injuries, and creating good colour contrast can enhance the visual perception levels. Our hypothesis was validated through both an experiment and a survey, paving the groundwork for more in-depth future research and fostering interest in using appropriate or preferred colours from a wider audience in sports. Applying appropriate colour principles to gymnastics mats, through selecting colours or colour combinations that offer strong contrast or stand out prominently, might enhance visual perception and assist the gymnasts in accurately identifying the mat's location, potentially reducing injuries.

AUTHOR CONTRIBUTIONS

Corresponding author, Dr. Ziho Kang, designed the experiment and survey. The second author, Mr. Cesar E. Gracia Salgado, conducted the experiment and survey, processed all collected data, and assisted in designing the experiment and survey. The third author, Ms. Sarah C. Gates, assisted in developing the structure of the article and conducting the statistical analysis. In addition, all three authors collaborated closely to analyse the data and compose all sections of the article.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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