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藍光對動態視力的影響

Blue-light Effects on Dynamic Vision

陳竑彣

Hung-Wen Chen

指導教授：葉素玲 博士

Advisor: Su-Ling Yeh, Ph.D.

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摘要

動態視力對於動物狩獵及人類生活都是不可或缺的重要能力，但目前關於如何增進動態視力的知識有限。先前研究已知藍光可能透過自發性感光視網膜神經節細胞(intrinsically photosensitive retinal ganglion cells, ipRGCs)增進人類的警醒能力，動物研究也發現 ipRGCs 對運動知覺敏感，因此推論藍光能影響與運動知覺有關的動態視力。本研究透過五個實驗探討藍光是否能增進人類的動態視力。動態視力共分成三項能力指標來檢視：眼動追蹤(eye pursuit accuracy, EPA，實驗一)、前後移動的立體動體視力(kinetic visual acuity, KVA，實驗一、二)、與水平上下左右移動的平面動體視力(dynamic visual acuity, DVA，實驗三到五)。EPA 能力由眼動追蹤時的凝視點與目標物間距離計算而得；KVA 是讓受試者在具有深度空間感的螢幕上觀看往前移的三個數字，並以階梯法測量速度敏感度；DVA 則為在同一平面上出現三個數字，並操弄不同方向(實驗三)、不同困難度(實驗四)、以及透過操弄 ipRGC 刺激量的藍光濾鏡測量是否為 ipRGCs 的貢獻。結果顯示藍光的確能夠增進 EPA，KVA 則是在藍光下表現較差，而 DVA 的藍光增進效果只出現在實驗三的向下運動以及實驗四的低對比度等困難作業的情況。此增進效果並非來自於 ipRGCs 的機制，至少在如實驗五的設備下無法被證實。本研究首次探討了藍光對於不同動態視力三種指標的影響，並發現藍光能夠在困難作業下增進動體視力中 DVA 的敏感度。

關鍵詞：藍光、自發性感光視網膜神經節細胞、動態視力、眼動追蹤、動體視力

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Blue-light Effects on Dynamic Vision

Hung-Wen Chen

Abstract

Dynamic vision is crucial to not only animals' hunting but also human activities, and yet little is known about how to enhance it, except for extensive training like athletics do. Exposure to blue light has been shown to enhance human alertness, perhaps through intrinsically photosensitive retinal ganglion cells (ipRGCs), which are sensitive to motion perception as revealed by animal studies. However, it remains unknown whether blue light can enhance human dynamic vision, a motion-related ability. We conducted five experiments under blue or orange light to test three important components of dynamic vision: eye pursuit accuracy (EPA, Experiment 1), kinetic visual acuity (KVA, Experiment 1 and 2), and dynamic visual acuity (DVA, Experiment 3-5). EPA was measured by the distance between fixation and target position when participants tracked a target dot. In the KVA task, participants reported three central target numbers (randomly chosen from 0-9) moving toward participants in the depth plane, with speed sensitivity calculated by a staircase procedure. In the DVA task, the three numbers were presented along the meridian line on the same depth plane, with motion direction (Experiment 3) and difficulty level (Experiment 4)

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manipulated, and a blue light filter lens was used to test the ipRGCs contribution (Experiment 5). Results showed that blue light enhanced EPA and DVA, but reduced KVA. Further, DVA enhancement was modulated by difficulty level: blue light enhancement effect was found only with hard task in the downward motion in Experiment 3 and with the low contrast target in Experiment 4. However, this blue light enhancement effect was not caused by mechanism of ipRGCs, at least not in the range we tested. In this first study demonstrating the relationship between different components of dynamic vision and blue light, our findings that DVA can be enhanced under blue light with hard but not easy task indicate that blue light can increase the sensitivity of dynamic visual discrimination when needed.

Keywords: *blue light, ipRGCs, dynamic vision, eye pursuit accuracy, dynamic visual acuity (DVA), kinetic visual acuity (KVA)*

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Introduction

Perceiving and analyzing moving objects in order to act immediately and appropriately is essential for survival, and this is true for animals as well as human beings from ancient times to nowadays. For animals and humans in ancient times, they chased preys or hid from predators by the ability called *dynamic vision*—vision for dynamic (constantly changing) stimuli—which is a matter of life and death. For us who have been safe from jungles in modern societies, we turn to use dynamic vision to perform better on sports or video games like shooting and car racing. Thus, another name has been given to this ability—*sports vision*, which includes not only dynamic vision but also hand-eye coordination. In addition, eye movements also play an important role on dynamic vision: When swatting a flying mosquito or a running cockroach, tracking the path of the insect is crucial, or else it will be missed.

Until now, there is still no clear and unified definition of what components should be included in dynamic vision. For the tests examined by ophthalmologists, for example, visual acuity, contrast sensitivity, stereo acuity, ocular alignment, and dominant eye are mostly tested with static stimuli; additional tests like accommodative, vergence, and near point convergence are tested with monocular or binocular ocular motor cues. Vision scientists, on the other hand, emphasize saccadic eye movements, visual reaction time, and peripheral awareness (Lee et al., 2016).

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Moreover, in sports field, dynamic vision contains static visual acuity, kinetic/dynamic visual acuity, contrast sensitivity, eye movement, focus flexibility, depth perception, visual reaction time, peripheral awareness, eye-hand-body coordination, and visualization (Loran & MacEwen, 1997; Wilson & Falkel, 2004). However, not all components have been fully researched, and no single ability can be completely separated from the others.

Since the many dimensions of dynamic vision complement each other, general abilities, rather than specific ones, should be paid more attention to. Here we list three key abilities critical for dynamic vision: eye movement, kinetic visual acuity, and dynamic visual acuity. To continuously and smoothly pursue the target with eye movements is important to track objects. At the same time, since objects are stereoscopic in real world, the ability to perceive motion in depth is also quite often used. One part of dynamic vision called kinetic visual acuity (KVA) is such an ability to analyze the objects moving forward and backward with respect to the horopter (i.e., the fixation plane). In addition, dynamic visual acuity (DVA) is the ability to perceive objects moving leftward, rightward, upward, or downward on the same fronto-parallel plane. Indeed, different brain regions were activated when participants conducted one of these tasks. For example, oculomotor nucleus in the midbrain contributes to eye movements, medial superior temporal (MST) contributes to KVA, and middle

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temporal visual area (MT/V5) contributes to DVA. Distinct mechanisms seem necessary for these different abilities essential for dynamic vision.

As dynamic vision is so important for survival and for sports, the question that how to enhance human dynamic vision becomes a hot issue, especially in sports/games that usually involve highly competitive situations and varieties of rewards. Human dynamic vision based on motion contrast reaches adult performance at the age of 15 (Schrauf et al., 1999). After reaching the peak, people usually improve dynamic vision by practicing to improve body-eye coordination reaction time, choice reaction time, and functional field (Ciuffreda, 2011; Schwab & Memmert, 2012). However, some researchers criticized and doubted the evidences of enhancing dynamic vision through training (Barrett, 2009; Lee et al., 2016). Aside from behavioral training, biological stimulation is another approach along with the advancement of technology. For example, Zito et al. (2015) tested the newly developed technique called high definition transcranial direct current stimulation (HD-tDCS) to replace the sponge electrodes in conventional tCDS, and discovered improvement in motion perception after cathodal HD-tCDS. Still, there are not many researches about this topic, and not yet a persuasive approach to enhance dynamic vision matures.

Previous studies have shown that blue light can enhance human cognition such

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as alertness, attention (Vandewalle et al., 2007; Viola et al., 2008), and working memory (Alkozei et al., 2016), as well as motion perception of mice (Zhao et al., 2014). Exposure to blue light affects human cognition through changing activations in some brain areas, particularly prefrontal brain regions that are associated with executive functions (Alkozei et al., 2016; Vandewalle et al., 2013). The biological mechanism behind blue light effect is via recently discovered intrinsically photosensitive retinal ganglion cells (ipRGCs, Berson, 2002). ipRGCs respond well to light, especially light with wavelength peaking around 480nm, but drive slow and sustained light responses (Wong et al., 2012). Though not acting on image forming functions, ipRGCs do help modulate the sensitivity of vision (Brown et al., 2012; Horiguchi et al., 2013; Spitschan et al., 2014), even in blind people (Vandewalle et al., 2013; Zaidi et al., 2007). In animal studies, ipRGCs also affect vision by modulating pupil size (Chen et al., 2011). Moreover, ipRGCs respond to moving stimuli, primarily slow to middle speed motion with every directions (Zhao et al., 2014).

However, how blue light affects human dynamic vision is still unknown. Based on the known mechanism of ipRGCs, we hypothesized that dynamic vision could be enhanced under blue light through the activation of ipRGCs – called the *ipRGCs hypothesis* here. Long and Garvey (1988) used four color lights (white, blue, yellow, and red) as targets on either dark or photopic background to measure dynamic visual

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acuity, and their results showed that only blue light on dark background enhanced DVA performance. They attributed the benefit of DVA under blue-light to S-cones, like the phenomenon of Purkinje shift that blue color looks brighter when dimly lit. Still, there is no direct biological evidence of this *s-cones hypothesis.* On the other hand, because human vision has poor temporal and spatial resolution under blue light (Cavanagh et al., 1987), perhaps dynamic vision would be impaired instead. Yet, different types of dynamic vision seem to have distinct effects from exposure to blue light.

In this study, we examined whether blue light could enhance dynamic vision and the mechanisms behind this enhancement if it exists. In Experiment 1, we started from two critical components of dynamic vision which are both essential abilities to perceive motion in real 3D world - eye movement and KVA, and KVA task was refined to eliminate masking effect in Experiment 2. In Experiment 3, DVA of upward and downward motion was measured to see how blue light affects yet another critical component of dynamic vision. Then, we further tested whether difficulty level of DVA could modulate the blue light effect in Experiment 4. Last, the *ipRGCs hypothesis* was tested in Experiment 5 by using a blue light filter lens.

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Experiment 1: Kinetic visual acuity (KVA) and Eye pursuit accuracy (EPA)

Kinetic visual acuity (KVA), the ability to perceive object moving toward or backward, is relatively important among various aspects of dynamic vision, because the object being tracked is usually changing positions in 3D space in reality. When animals hunt their preys or when human follows a tennis ball, the tracers commonly try to move themselves closer to the target, in order to increase the target's visual resolution. In the meantime, tracers also need to move their eyes promptly to keep their target in the visual field, requiring the ability called *eye pursuit accuracy (EPA).*

In Experiment 1, we conducted two experiments: KVA and EPA under two different background colors on the monitor: blue light and control light. Orange was determined to be the control light due to its far distance from blue on the color spectrum, but not biased by the stereotypes of some colors like red light which increases alertness at night (Figueiro et al., 2009) and serves as a stop or warning signal (Funke, 2010)

Method

Participants. Sixteen young male adults took part in this experiment (aged from 19-35 years, average = 25.9), all with normal or corrected-to-normal binocular vision using Landolt C vision test. Females, who have menstrual cycles and it has been shown that endocrine system could be affected by ipRGCs activation (Hanifin &

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Brainard, 2007; Parry et al., 1997), were excluded to avoid uncertain variances like short-interval timing (Morita et al., 2005) that might bias the speed judgment. Also, the age was constricted between 18-35 years old to prevent visual immature or degeneration. To ensure that performances of dynamic vision were free from being affected by visual acuity, participants were all passed the Landolt C vision test (criterion: 20/20) with naked eyes or corrected vision. Participants signed the written informed consent before the experiment, and were financially reimbursed for their two-day participations. The study was approved by the Research Ethics Committee at the National Taiwan University (REC code: 201505HS071).

Apparatus. Participants were seated in a dimly lit room with their head placed on a chin rest 60cm from the i-TECH 20" CRT monitor, in front of which was the EYELINK 2000 eye tracker (SR Research, Mississauga, Ontario, Canada) with 1000 Hz resolution. All stimuli in Experiment 1 were presented on the screen with spatial resolution of 1024 x 768 pixels at 100 Hz refresh rate. Background colors were either blue (luminance: 6.560 cd/m^2, CIE: 0.1463, 0.0695) or orange (luminance: 6.787 cd/m^2, CIE: 0.5843, 0.3703), measured by Photo Research Inc's PR 655 (Figure 1). From participants' view, every single pixel was about 0.037°. All programs in this study were written and presented with MATLAB 8.1 version (The MathWorks) and psychtoolbox 3 version.

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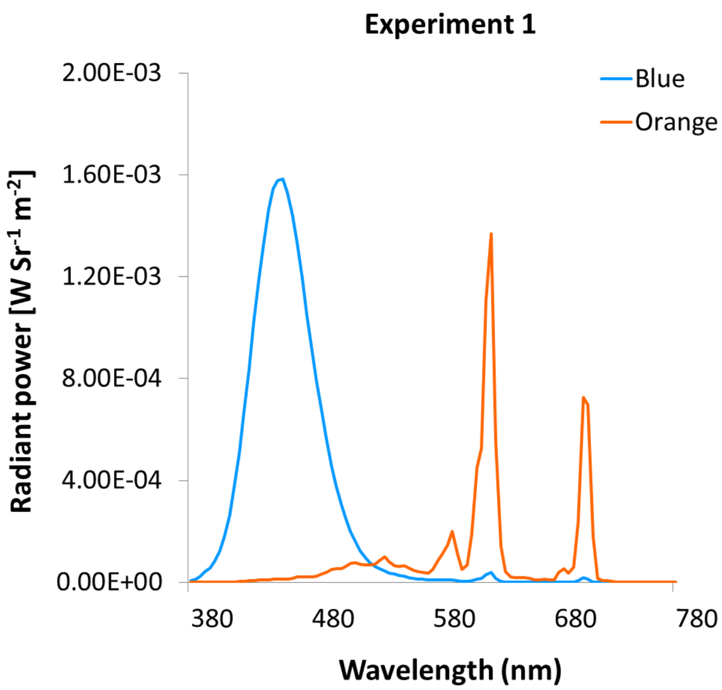

Figure 1. Spectra of background colors in Experiment 1. The spectra of blue and orange background colors used in Experiment 1 were presented by wavelength (x-axis) and radiant power (y-axis).

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Stimuli and Design. Two tasks were performed: KVA and EPA.

Kinetic Visual Acuity (KVA). A pattern of blue or orange background with white grid (0.037° of each line) served as depth cue (Figure 2) was presented on the monitor, creating a virtual space of $12m^3$ behind the screen by means of projection matrix in OpenGL in MATLAB (OpenGL Wiki, 2017). Three black randomly chosen numbers (0-9) appeared when participants pressed the space key, and the numbers were enlarged from about 0.91° to 18.43°of visual angle, simulating a 20 cm high object that initiated from 12m away behind the screen and moved toward the participants. In each trial, three moving and enlarging numbers each sequentially changed to its next number in 5 cycle with the fixed order every 80cm in the simulated space.

A one-up one-down staircase procedure was used to measure the KVA sensitivity: moving numbers speeded up when participants responded correct numbers no matter what sequential was, and speeded down when they responded any incorrect numbers. The initial speed was 8 m/s, and the step size was 0.5 m/s. There were eight reversals in each staircase, and participants finished six staircases. Only the average of last six reversals in each staircase and the last five staircases were included in the calculation of the speed sensitivity (Levitt, 1970).

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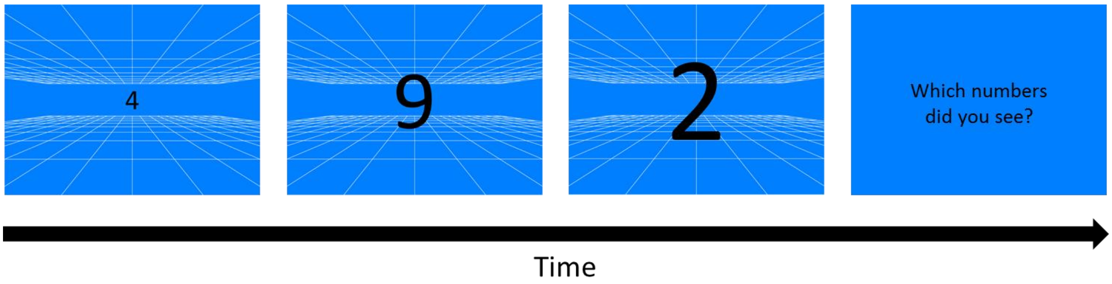

Figure 2. Procedure of KVA (an example in the blue light condition). A pattern of white grid was drawn on the blue background as a depth cue for participants to build a 12 m^3 virtual space behind the screen. Whenever participants pressed the space/start key, three randomly chosen one-digit numbers would appear from the middle of the display, and enlarge and sequentially change the numbers in cycles. As the numbers disappeared, three numbers reported by participants were typed by the experimenter.

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Eye Pursuit Accuracy (EPA). A black dot with 0.74° diameter was moving from the center after participants pressed the start key. The moving dot started at the speed of 7.4 deg/sec, increased 3.7 deg/sec per second in the first 20 sec, and after that, increased 1.85 deg/sec every sec. The dot always went straight, changing its direction randomly every 0.3~2 sec (jittered) or when the dot hit the boundaries of the screen (Figure 3).

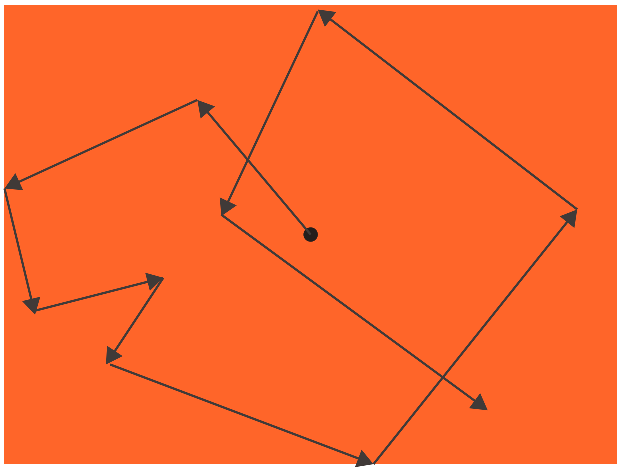

Figure 3. Procedure of EPA (an example in the orange light condition). A black dot moved with a changing speed from slow to fast, increasing its speed every sec and randomly changing its speed every 0.3~2 sec or when hit the boundaries. Participants' task was to keep their fovea on the dot as precisely as they could, and their eye movements were recorded by Eyelink 2000.

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Procedure. Participants were randomly assigned to do the experiments in one of the two counterbalanced conditions: background colors (blue/orange) and task orders (KVA/EPA). Since we aimed to test how different background colors affect dynamic vision, participants conducted the experiment under blue/orange light on the first day and the other background color on the next day. This manipulation was to make sure that the results were not due to practice effect—better performance on the second day. Moreover, we were also interested in participants' general dynamic vision ability, by analyzing the correlation between KVA and EPA tasks, the order of the two tasks was also counterbalanced across participants.

After tested their left-eye, right-eye, and binocular visual acuity by Landolt C test, participants were seated in the dimly lit room for a 5-min light adaptation. It took 5 minutes to adapt to the same background colors as when with task, in order to activate slow-adapted ipRGCs (Wong et al., 2012). During adaptation, participants orally answered a questionnaire about their exercise and video game playing habits while opening their eyes toward the screen. Afterwards, participants began the experiment from either KVA or EPA.

In the KVA session, participants saw the grid on the background color, and then they were asked to press the space bar to start. After each trial, the experimenter was told what numbers participants saw and typed them for the participants, because the

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number keys on the keyboard were not separated from other irrelevant keys, which might lead participants to press the wrong key in a dimly lit room.

In the EPA session, nine-point calibration and validation procedure were administered before starting the EPA experiment. Participants' left eye was tracked by the eye tracker with a sampling rate of 1000Hz, and they were asked to stare at the central dot when pressing the space bar to start the trial. Before each trial, the experimenter checked the status of eye tracker to make certain that participants' eye movements were recorded precisely. Participants were instructed to pursue the moving dot by fixating it as possible as they could, without using corner of their eyes to pursue. Three 45-sec pursuit trials were conducted, and participants took self-paced break at least 90 sec between two trials.

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Results

Kinetic Visual Acuity (KVA). Two-tailed paired t-test was calculated by SPSS to examine whether KVA performances differed in blue and orange background colors (Figure 4). Average speed sensitivity of KVA under blue light was 19.70 m/s ± 3.247, and it was 21.79 m/s ± 4.426 under orange light. The result showed that KVA was significantly better under orange than blue background color ($t(15) = -2.841$, $p = .012$).

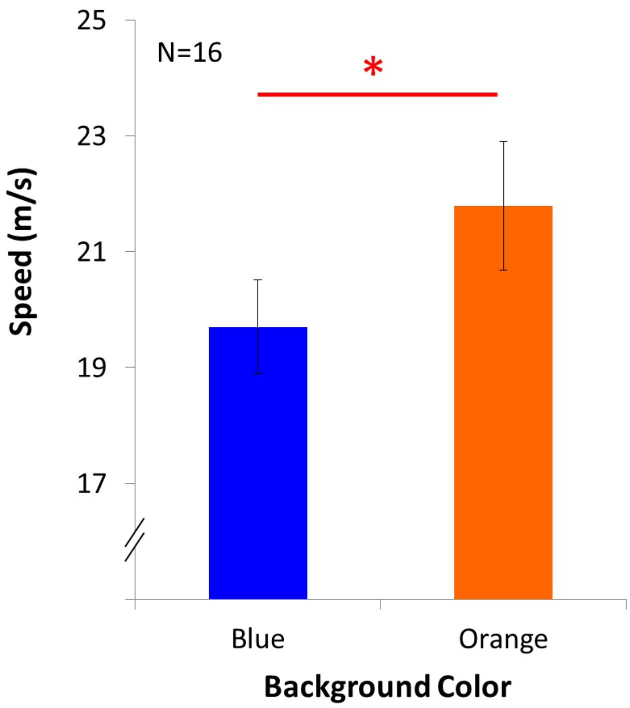

Figure 4. Results of KVA. Two colored bars represent the average speed, where y-axis indicates, under blue or orange light condition. Error bars represent one standard error from the mean.

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Eye pursuit Accuracy (EPA). The average overall, x-axis-only and y-axis-only shortest distance between the target dot and the eye position of every frame in three trials were calculated (Figure 5). We separated X-axis-only and y-axis-only distances from the overall distance because different mechanisms underlie horizontal and vertical eye pursuit (Rottach et al., 1996). Two-tailed t test was done to compare the distance under blue and orange light. In the EPA task, average overall distance was 10.42 deg. ± .11 under blue light, significantly shorter than 10.53 deg. ± .10 under orange light ($t(15) = -2.243$, $p = .040$, Figure 5A). It implied that EPA was better under blue light, because of the shorter eye-dot distance, than orange light. Furthermore, the y-axis-only distance was 6.24 deg. ± .07 under blue light, marginally shorter than 6.37 deg. ± .06 under orange light ($t(15) = -1.837$, $p = .086$, Figure 5C). Nevertheless, on the x-axis-only distance, it was 7.02 deg. ± .09 under blue light, which was no difference with 7.04 deg. ± .09 under orange light ($t(15) = -.449$, $p = .660$)..

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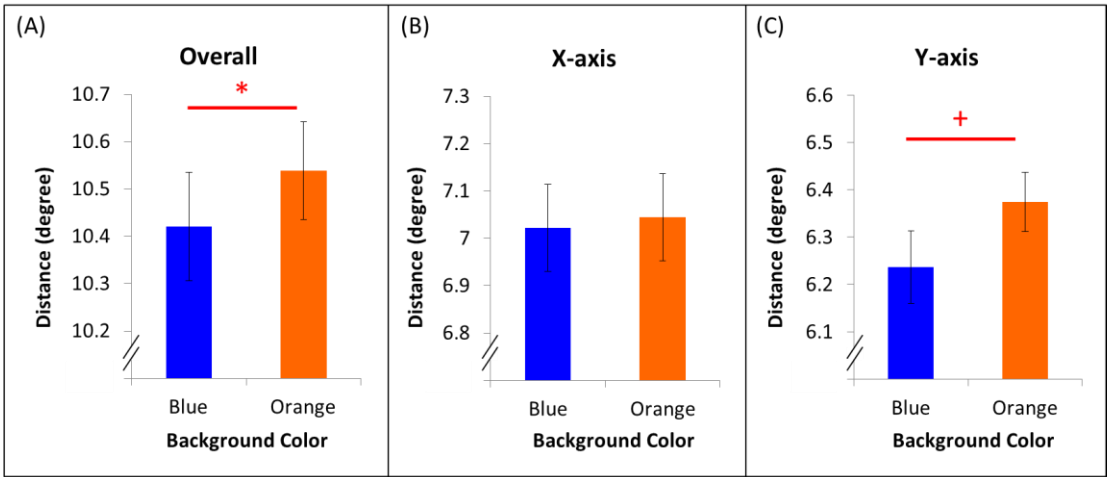

Figure 5. Results of EPA. Different colored bars stand for the average distance under blue/orange light. Error bars represent one standard error from the mean. The * mark indicates significant result (p < .05), whereas the + mark, marginally significant (p < .10). (A) The average of overall distance was calculated as the mean of the shortest distance between eye position and dot position every 10 ms in three trials. (B) X-axis-only distance was the average of the shortest horizontal distance between fixation and the dot. (C) Y-axis-only distance was computed as (B) but with shortest vertical distance.

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Correlation between KVA and EPA. We were interested in the relationship between KVA and EPA, in order to test whether performances of KVA were correlated with EPA patterns, since these two are critical components of dynamic vision. Bivariate correlation of SPSS was used to compute the Pearson correlation, shown in Table 1. Under blue light KVA was significantly correlated with overall (r = -.550, p = .027) and y-axis-only distance (r = -.535, p = .033), while KVA was marginally correlated with x-axis-only distance (r = -.465, p = .069). However, there were no correlations for the three situations under orange light.

The performances under blue light and orange light were combined to see the general ability of dynamic vision of each participant. We observed that KVA had significant correlation with y-axis-only distance (r = -.574, p = .020) and marginal correlation with overall distance (r = -.483, p = .058).

Table 1

Correlation Between KVA and EPA

Condition	overall	x-axis	y-axis
Blue light	-.550*	-.465^{+}	-.535*
Orange light	-.377	-.340	-.296
Average	-.483^{+}	-.361	-.574*

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Questionnaire. We conducted the same questionnaire of the exercise and video game playing habits of types and frequencies in every experiment of this study. However, no correlation was found, so it would not be mentioned in the following experiments.

Discussion

KVA results were better under orange light; on the contrary, EPA results were better, especially with shorter y-axis distances, under blue light. Furthermore, KVA performances were related to distance of EPAs with respect to the target dot.

KVA and critical flicker fusion threshold (CFFT). For KVA, speeding up stimuli required higher temporal resolution, which was in connection with critical flicker fusion threshold (CFFT). By measuring at which flicking rate could a participant see as a constant light under different colors, Brindley et al. (1966) found that CFFT could only be impaired under blue light. Perhaps, it was not “enhanced” KVA performance under orange light, but “impaired” KVA performance under blue light due to poorer CFFT.

Eye Pursuit Accuracy (EPA). Results of EPA under blue light showed shorter overall and y-axis-only distances, but no difference in the x-axis-only distance. Rottach et al. (1996) tested the horizontal and vertical eye pursuit, and discovered that

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horizontal pursuit was better when predictable wave forms were used, while vertical pursuit had greater eye accelerations when initiation of pursuit was tested. Since the dot in this present experiment moved randomly like the initiation condition in Rottach et al., it showed a similar pattern that the target-eye distance was shorter in y-axis than in x-axis, suggesting that horizontal and vertical eye pursuit were separately controlled.

KVA and EPA. The correlation between KVA and EPA as shown in table 1 was similar between (1) the blue light condition and (2) general dynamic visual ability when results under blue light and orange light were combined (i.e., "average" in table 1). Yonehara et al. (2009) found that cells in medial terminal nucleus, the principal nucleus of the accessory optic system receiving signals from direction-selective ganglion cells in the retina coding direction of image motion, only were activated by optokinetic stimuli (crucial for eye pursuit) of vertical motion. This may be the reason why vertical pursuit was found more important for dynamic vision here.

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Experiment 2: KVA without masking effect

The stimuli of the KVA task used in Experiment 1 were covered by another number in a short time interval, inducing a masking effect that one number might have masked another. Since human's temporal resolution was poor under blue light (Cavanagh et al., 1987), perhaps it triggered a greater masking effect under blue light than under orange light, leading to the results of better KVA under orange light in Experiment 1. Hence, in this experiment, we aimed to measure the KVA sensitivity without numbers being masked. To eliminate the spatial masking effect, we separated the targets of three numbers in different positions (up, left, right) on a same object – a moving cube. The virtual space was created by the white grid by means of OpenGL, and the appearing time of each numbers was the same as that in Experiment 1. In this way, we controlled the appearing time interval of targets and the task of discriminating and memorizing three numbers, but isolated three numbers in three positions to get rid of the potential masking effect which led to the results in Experiment 1 highly associated with temporal resolution and critical flicker fusion threshold. In Experiment 2, we only conducted the modified KVA task.

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Method

Participants. Another group of 16 male participants aging between 19~32 (average = 23.9 yrs) were recruited, all with normal or corrected-to-normal binocular vision, and signed informed consent before the experiment.

Apparatus. Participants were seated in a dimly lit room with their head on a chin rest at a distance of 60cm from a 27” LED screen (EIZO FORIS FS2735 QHD FreeSync), also used in the following experiments. Background colors were either blue (luminance: 6.163 cd/m^2, CIE: 0.1454, 0.0544) or orange (luminance: 6.306 cd/m^2, CIE: 0.6173, 0.3605), measured by Photo Research Inc’s PR 655 (Figure 6). All stimuli were presented on the screen with spatial resolution of 1020 x 768 pixels at 120 Hz refresh rate. Under this setting, each pixel was about 0.037° at the viewing distance of 60 cm.

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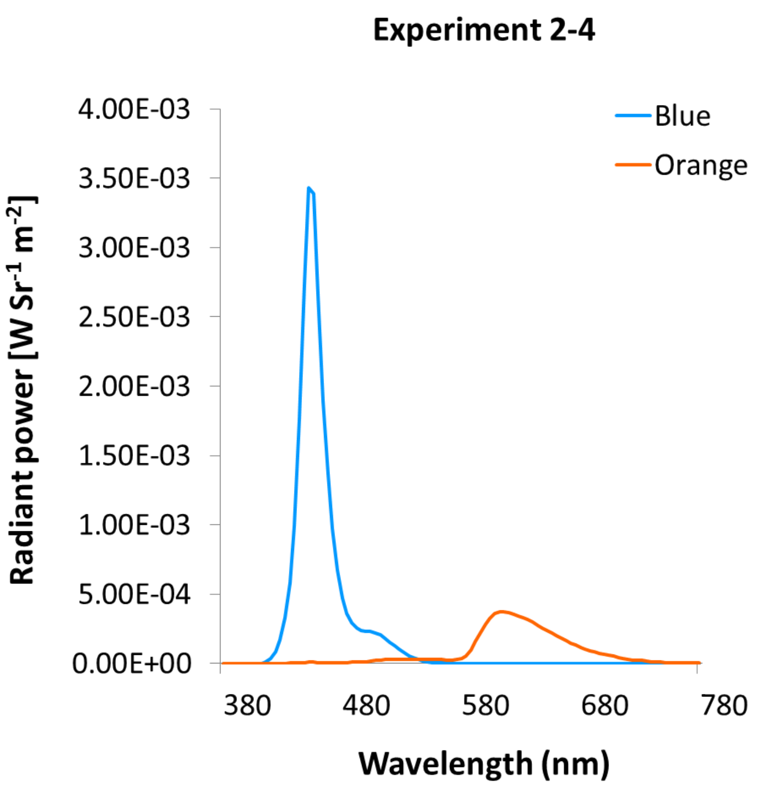

Figure 6. Spectra of background colors in Experiment 2-4. The spectra of blue and orange background colors used in Experiment 2-4 were illustrated by wavelength (x-axis) and radiant power (y-axis).

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Stimuli and Design. The same white grid as in Experiment 1 was presented on either blue or orange background colors as depth cue and created a virtual space of $12m^3$ (Figure 7). To avoid masking effect, three black randomly chosen numbers (0-9) were printed at up-, left- and right-position on the front of a 30 cm^3 cube, with 13.3 cm height each, and the cube was enlarged from about 1.36° to 26.57°of visual angle, which looked like a cube moving from 12 m toward participants. In each trial, three numbers on the cube appeared sequentially with the order of up-, left-, and right-position, and changed in 5 cycle with the fixed order every 80cm in the simulated space, replicating the time intervals as the stimuli in Experiment 1. After a trial, participants reported the three numbers in the same order as the appearing order: up, left, right. The answer was regarded as wrong when the numbers or the order were different from the stimuli.

The sensitivity was calculated by one up one down adaptive staircase procedure, with 8 reversals in 6 staircases each. The initial speed was 23.26 m/s, and the maximum speed was 116.28 m/s, with the step size of 3.49 m/s before the second reversals, the step size of 1.16 m/s between second and third reversal, and that of 0.58 m/s after the third reversal. The final sensitivity was the average of last 6 reversals of every staircase excluded the first one.

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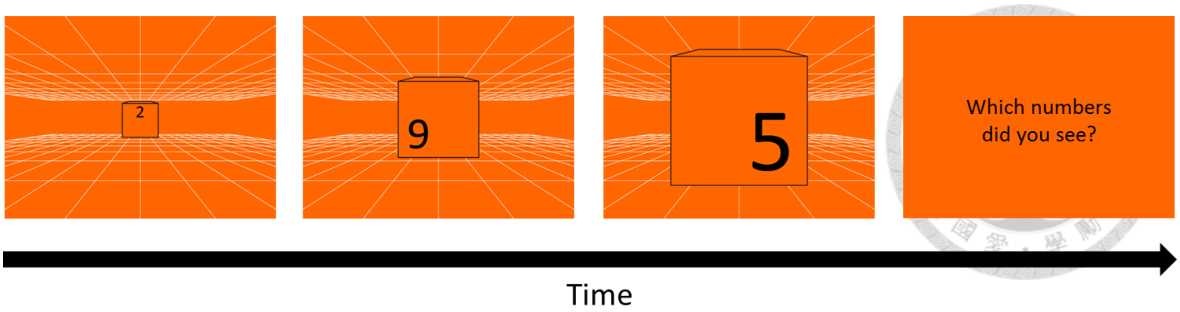

Figure 7. Procedure of KVA without masking effect. Three randomly chosen numbers (13.3 cm height) repeatedly appeared in the order of up-, left-, and right-position for 5 cycles on a 30 cm^3 cube moving from 12m toward participants. After each trial, participants had to report the three numbers in the same order as their appearing order (up, left, right). A one up one down adaptive staircase procedure was used to calculate the sensitivity of KVA: speed up when participants answered correctly and speed down when answered wrongly, in terms of either the numbers or the order.

Procedure. Participants were randomly assigned to conduct the experiments under either blue or orange background color on the first day. As in Experiment 1, after their monocular and binocular visual acuity tested by the Landolt C task, participants were instructed to be seated in a dimly lit room for 5-min adaptation. Then, white grid appeared on the background color, and participants pressed the space bar to start when they were ready. After each trial, participants typed the three numbers sequentially by pressing the number keys on the keyboard.

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Results

The same two-tailed paired t-test as in Experiment 1 was computed by SPSS to test whether KVA performances were still better under orange light than under blue light (Figure 8). Average speed sensitivity under blue light was 60.79 m/s ± 3.81, and it was 79.82 m/s ± 4.37 under orange light. The results showed that despite the withdrawal of the masking effect, KVA was still significantly better under orange background color than blue one ($t(15) = -6.531$, $p = .000$).

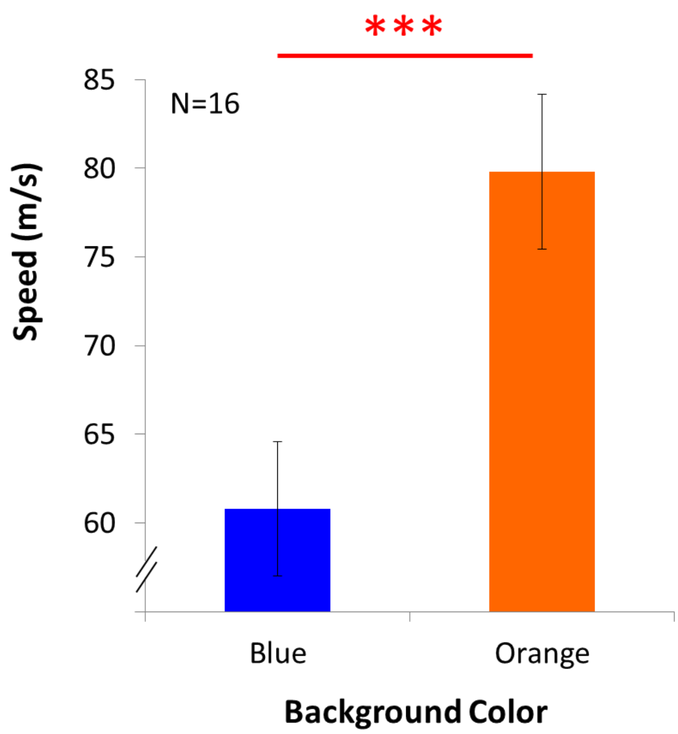

Figure 8. Results of KVA without masking effect. Two bars represent the sensitivity of KVA under blue and orange light. Y axis indicates the average speed sensitivity.

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Discussion

The results showed the same effect of better KVA performances under orange light than under blue light, like the results in Experiment 1, indicating that indeed KVA impairment under blue light was not due to poor temporal resolution and lower CFFT as demonstrated by Brindley et al. (1966). Therefore, how could blue light affect differently on KVA task and EPA task in Experiment 1? In the KVA task, participants had to do more than just following the target like in the EPA task. We therefore tested whether the distinctions of blue light effect on these two tasks were due to the task itself.

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Experiment 3: Dynamic Visual Acuity (DVA)

In Experiment 1, the blue light enhancement effect was found only in the EPA task, and not the KVA task. The differences between these two tasks were that EPA was the ability to track objects on the same plane, without discriminating numbers and memorizing them as in the KVA task. To clarify that the results of EPA task could represent the ability of dynamic vision on the same plane, we conducted an experiment similar to KVA but on the same depth plane, so-called dynamic visual acuity (DVA), in Experiment 3.

We followed and modified the paradigms used to measure DVA in previous studies. Ludvigh and Miller (1958) started to use a measure similar to static vision test, which Brown et al. (1972) refined as projecting moving Landolt C on a white screen 1.5m far from observers. AtheleVision, a software made by a Japanese vision scientist Hisao Ishigaki, used a ball with numbers printed at different locations of the ball rolling at the center to test DVA of athletics (Liu et al., 2010). We used central moving numbers without the rolling ball and two vertical lines were added instead.

In order to examine participants' DVA, not only detection of motion but discrimination of objects should be tested, just like KVA in Experiment 1. In Experiment 3, we examined whether DVA of upward and downward motion could be affected under blue light. On account of finding that blue light affected more on y-axis

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pursuit in Experiment 1, only vertical motion was administered in this experiment.

Method

Participants. Twenty four males were recruited (aged from 20-34, with average 24.5 years old). Vision, age, and gender of all participants met the same criteria as in Experiment 1. The written informed consent was collected from every participant before the experiment started.

Apparatus. The same blue and orange background colors were displayed on the LED monitor as in Experiment 2, which was at a distance of 80cm from the participants. All stimuli in this experiment were presented on the screen with spatial resolution of 1920 x 1080 pixels at 120 Hz refresh rate, making each pixel being about 0.021° from participants at a viewing distance of 80 cm under this setting. The apparatus was the same in Experiment 4 and 5 as well.

Stimuli and Design. A square (22.72° x 22.72°) in blue or orange color as background was displayed during the whole experiment. Three randomly chosen numbers (0-9, size 1.89°) moved sequentially in either upward or downward direction at the center of the display, between two vertical black lines at a distance of 4.536° (Figure 9A and 9B). The number appeared on the monitor one at a time, changing to the next number when it had moved a distance of 7.573° (1/3 of the monitor).

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Participants' task was to report the numbers in the same order as they appeared. A one-up one-down adaptive staircase procedure was used with eight reversals for one staircase and six staircases in each condition. The initial moving speed was 19.8 deg/sec, and the step size was 2.97 deg/sec before the first reversal, 0.99 deg/sec between the first and second reversal, and 0.495 deg/sec after the second reversal.

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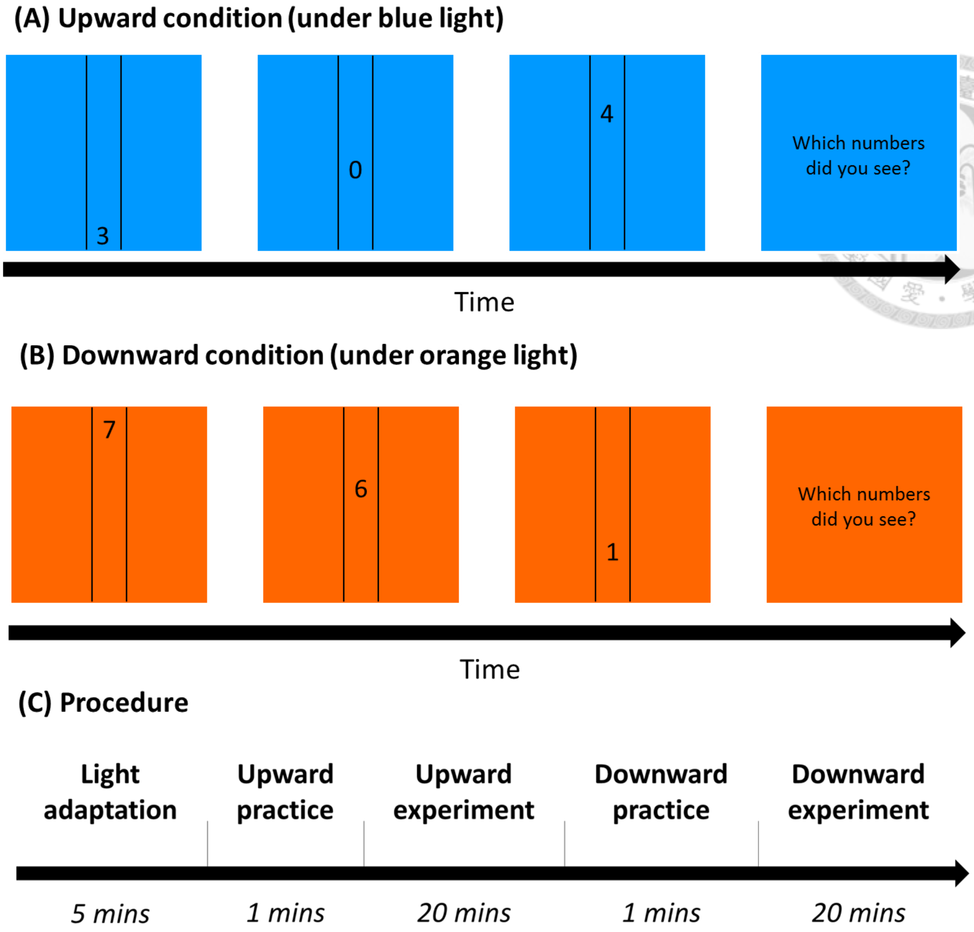

Figure 9. Procedure of DVA. (A) Upward condition (an example under blue light): 3 randomly chosen numbers sequentially moved between two vertical lines from down to up on a blue square as background color. After the trials, participant had to report the three numbers in the same order as they were presented. (B) Downward condition (an example under orange light): Similar to (A), but numbers moved from up to down with an orange background. (C) The procedure of DVA on each day for two days: After 5-min blue/orange light adaptation (the same color as the task), participants practiced correctly for 5 trials and then conducted the DVA task in either the upward or downward condition (this figure shows the upward condition first), and did the other condition afterwards.

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Procedure. A 2 (background color: blue/orange) × 2 (direction order: upward/downward) within-subject design was used, and all conditions were randomly assigned to the participants across participants. Participants underwent the vision test and then were seated in a dimly lit room for light adaptation for 5 minutes. After the adaptation, participants began the six staircases of upward/downward DVA after practicing, and then finished the other direction of practice trials and formal experiment (Figure 9C). In each trial, the colored background square and the black vertical lines were shown on the monitor, and not until participants pressed the space/start bar would the target numbers appear to move. Then, participants typed the three numbers they saw in the same order as the stimuli appeared. If participants reported correct numbers but with a wrong order, then the answer would be regarded as wrong and the speed of the next trial would be decreased.

Results

Two-way ANOVA was computed using SPSS, with two factors light (blue/orange) and direction (upward/downward). Figure 10 showed that the performance was better under blue light than under orange light ($F(1,23) = 6.415$, $p = .019$*, $\eta^2 = .218$), and better with upward direction than downward direction, as expected ($F(1,23) = 33.831$, $p < .001$***, η^2 =595). However, there was a marginal interaction between light and direction ($F(1,23) = 4.175$, $p = .053$, $\eta^2 = .154$). In the

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upward condition, average DVA speed sensitivity was 34.12 degree/sec ± 1.38 under blue light, no difference with 33.87 degree/sec ± 1.15 under orange light. However, in the downward condition, average speed was 30.69 degree/sec ± 1.02 under blue light, significantly higher than 28.96 degree/sec ± 0.70 under orange light (post hoc: $p = .004$). We found that blue light only enhanced DVA with downward motion, but not with upward motion.

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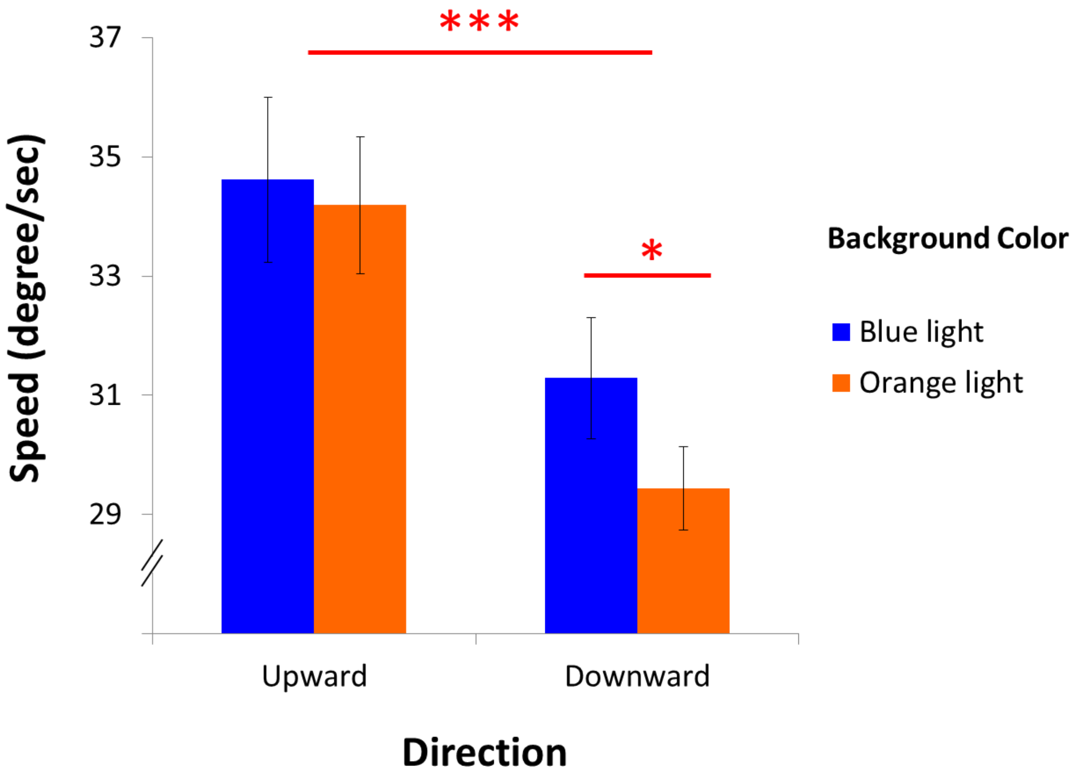

Figure 10. Results of DVA. X-axis shows directions of upward and downward condition, and y-axis indicates sensitivity for speed. Blue bars represent the average speed sensitivity under blue light, and orange bars average speed sensitivity under orange light, with standard errors as error bars.

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Discussion

Performance of DVA was better under blue light than under orange light, which was consistent with the result of EPA in Experiment 1. Taken together the results from Experiment 1 and 3, this showed that blue light indeed enhances dynamic vision on the same plane, but not on the perception of motion in depth. In the KVA task in Experiment 1 and 2, participants had to memorize the three numbers continuously displayed in cycle, requiring more capacity than the EPA task, in which participants merely looked at the moving dot. However, in the DVA task in Experiment 3, participants should memorize three numbers presented like in the KVA task, and still showed blue the light enhancement effect as obtained from the EPA task. Thus, the opposite blue light effects in Experiment 1 (i.e., *enhancement* in EPA and *impairment* in KVA) may not be due to different strategies participants used or differences in memory capacities between EPA and KVA. Rather, it should be due to the difference in 2D vs. 3D space.

Also, our DVA result echoed that in Long and Garvey (1988), that DVA was better under blue light among other colors in the dark-adapted condition. In the current study, the speed sensitivity in the upward condition was higher than that in the downward condition, which was also discovered in Seya et al. (2015) who used random-dot patterns and found that vection magnitude was larger in upward motion

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than downward motion.

In summary, higher speed sensitivity was found under blue light than orange light, especially with downward motion, indicating better performance with downward motion under blue light than orange light. However, we wondered that why the blue light enhancement effect occurred only in the downward condition. Since performance in the upward condition was better, we hypothesized that upward DVA was an easier task, compared to downward DVA. Hence, in Experiment 4 we tested whether difficulty level of task could modulate the blue light enhancement effect.

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Experiment 4: DVA with Difficulty Level Manipulated

In this experiment, we aimed to investigate whether difficulty level indeed affects the enhancing DVA effect of blue light. Previous studies have shown that taking an easy task requiring only little capacity (kahneman, 1973), which may lead to small or no effect on what we operated. We conducted easy and hard task with the same upward direction as in Experiment 3, but changed contrast of the moving numbers to reduce the visibility by lowering the contrast (Robson, 1966). Thus, we decreased the target-background contrast by changing the black numbers to gray, which we called a hard task. The original condition of black numbers was called an easy task.

Method

Participants. Another group of 16 males were recruited (aged from 19-29, with average 22.5 years old). All participants were met with the same criterion of participants in Experiment 3.

Stimuli and Design. All stimuli and design were as the same as in Experiment 3: three moving numbers were presented between two vertical lines. However, in this present experiment, only the upward condition was conducted. To increase the difficulty level, we adjusted the luminance of the moving numbers to gray (1.58 cd/m^2,

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CIE: 0.3124, 0.3192). The luminance of black numbers was nearly 0. Michelson contrast (max - min) / (max + min) was 59% for the hard task of gray numbers, and 100% for the easy task of black numbers.

Procedure. As in Experiment 3, participants conducted the experiment with blue or orange background colors in two separated days of the same time period. Each day after a 5-min light adaptation (same with the background colors) and practice trials, participants conducted either the easy or hard task.

Results

We analyzed a two-way ANOVA with two factors, light (blue/orange) and difficulty (easy/hard). The results (Figure 11) showed that there were no significant main effects (light: $F(1,15) = 1.219$, $p = .287$, $\eta^2 = .075$; difficulty: $F(1,15) = 3.268$, $p = .091$, $\eta^2 = .179$). However, there was interaction between light and difficulty ($F(1,15) = 4.609$, $p = .049$, $\eta^2 = .235$). Hence, post hoc test (LSD) was estimated as below: in the easy task, the average speed was 36.16 deg/sec ± 1.32 under blue light, not different from 36.39 deg/sec ± 1.46 under orange light; in the hard task, the speed sensitivity was 36.52 deg/sec ± 1.46 under blue light, significantly higher than 34.33 deg/sec ± 1.23 under orange light (post hoc (LSD): $p = .032$).

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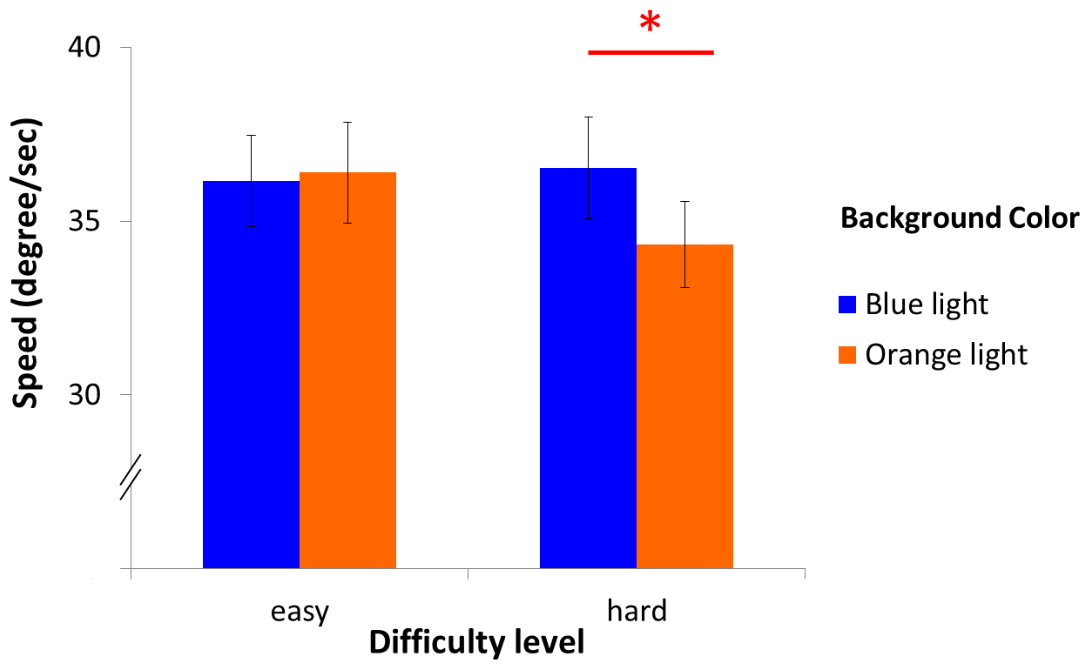

Figure 11. Results of DVA in two difficulty levels. The x-axis showed whether the bar was of easy or hard task, while y-axis depicts the speed. Again, colored bars represent what background color was, and the error bar was computed as standard error.

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Discussion

Dynamic visual acuity can be enhanced under blue light only with hard task but not easy task. It indicates that the lack of blue light enhancement effect in upward motion in Experiment 3 may be due to its easiness, but not due to different mechanisms between upward and downward motion.

Although the difficulty level manipulation was only marginally significant, there was a possibility that the facilitation in the hard task was so immense that it reached the performance in the easy task. Because in both tasks, participants only conducted upward condition, not downward condition like in Experiment 3, it may result in a larger practice effect.

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Experiment 5: DVA with ipRGCs level manipulation

In Experiment 3, we found that DVA was better under blue light. In this experiment, we tested whether it was due to ipRGCs. To examine the effect of ipRGCs, a blue-light filter lens was used to filter out half of the ipRGC activation while keeping the color and luminance the same (Shih et al., 2016).

Method

Participants. A different group of 16 young male adults were recruited (aged from 19-28, with average 22.38 years old), with three participants having their left eye as dominant eye. Participants looked from their own hands holding a circle by either left or right eye to test which was their dominant eye, by which was asked to look through the filter lens.

Apparatus. This experiment followed the setting in Experiment 3, but with an adjustable goggle added on the chin rest (Figure 12A). There were two hollows on the goggle that could place two lenses according to different conditions. In the no-filter condition, participants watched the screen directly through the hollow with their dominant eye, and were blocked with a black filter with their non-dominant eye. In the filter condition, a filter lens, which could filter out the light wavelength from 488 nm to 514.5nm, was equipped at participants' dominant eye to lower the ipRGCs

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activation level to half of that in the no-filter condition (Shih et al., 2016). To equate the luminance and the color of background color in the two conditions, gray (RGB: 128, 128, 128) was used in no-filter condition (Figure 12B), and celadon (RGB: 136, 188, 170) in the filter condition (Figure 12C). This celadon was determined using the functions in Shih et al. (2016) to let participants look through the filter lens the same as gray. Besides, the luminance was similar in the two conditions (22.36 cd/m^2 and 23.16 cd/m^2, measured by Photo Research Inc's PR655, Figure 13).

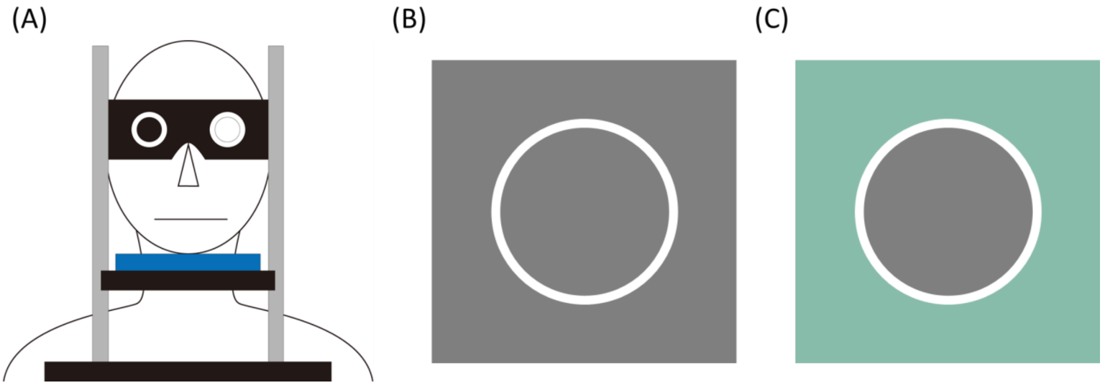

Figure 12. Apparatus of DVA with filter. (A) A goggle with two hollows was equipped on a chin rest. Participants looked through the hollow with their dominant eye, and their non-dominant eye was blocked by a black lens. The location of lens was changeable, so that it could fit different conditions and participants' dominant eye. (B) No-filter condition: the square was what displayed on the screen, and the circle was what participants looked directly through the hollow of the goggle. (C) Filter condition: the screen displayed a celadon square, and was looked as gray through the filter lens.

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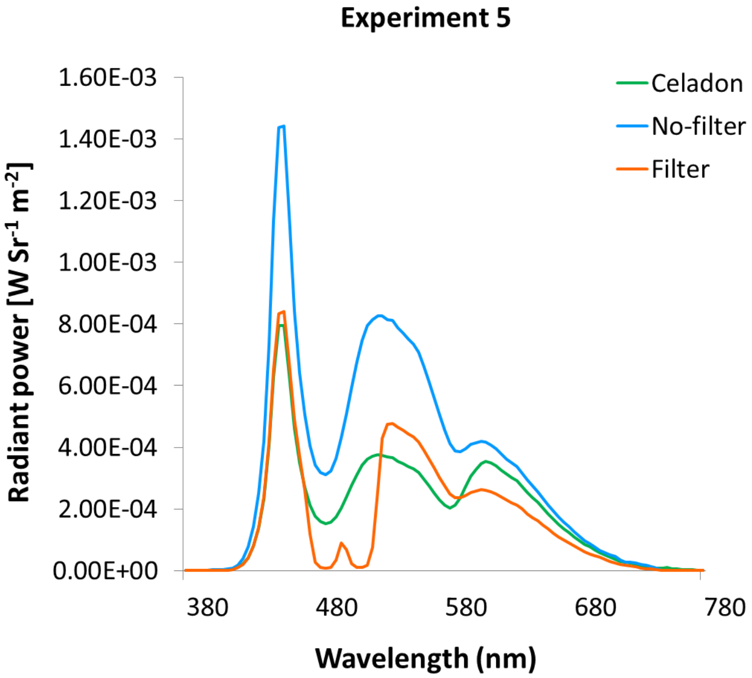

Figure 13. The spectra of the background colors used in Experiment 5. It is illustrating by wavelength (x-axis) and the radiant power (y-axis). The green line represents the color spectrum of the original celadon color; the blue line indicates that of gray color in the no-filter condition; and the orange line depicts that of gray color looked through filter in the filter condition.

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Stimuli and Design. All materials and design were the same as in Experiment 2, except that the condition of background color was substituted to gray (no-filter) and celadon (filter). Hence, a 2 (lens: no-filter/filter) × 2 (direction: upward/downward) within-subject design was conducted.

Procedure. The procedure was similar to that in Experiment 2; however, we tested the participants' vision only for their dominant eye. Before going into the dimly lit room, the goggle was already set, so that participants did not know which condition it was. Participants were instructed to sit still and to look out from their dominant eye during adaptation and the whole experiment.

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Results

Two factors were manipulated in the ANOVA test (Figure 14): lens (no-filter/filter) and direction (upward/downward). In the upward condition, the average speed was 34.28 deg/sec ± 4.22 under the no-filter condition, and 34.86 deg/sec ± 5.55 under the filter condition. In the downward condition, the average speed was 29.40 deg/sec ± 3.09 with no filter, and 29.60 deg/sec ± 4.04 with filter. There was only the main effect of direction, showing that performance in upward motion was better than downward motion ($F(1,15) = 70.274$, $p < .001$, $\eta^2 = .824$). No main effect on lens ($F(1,15) = .247$, $p = .626$, $\eta^2 = .016$) and no interaction between lens and direction ($F(1,15) = .079$, $p = .782$, $\eta^2 = .005$) were observed.

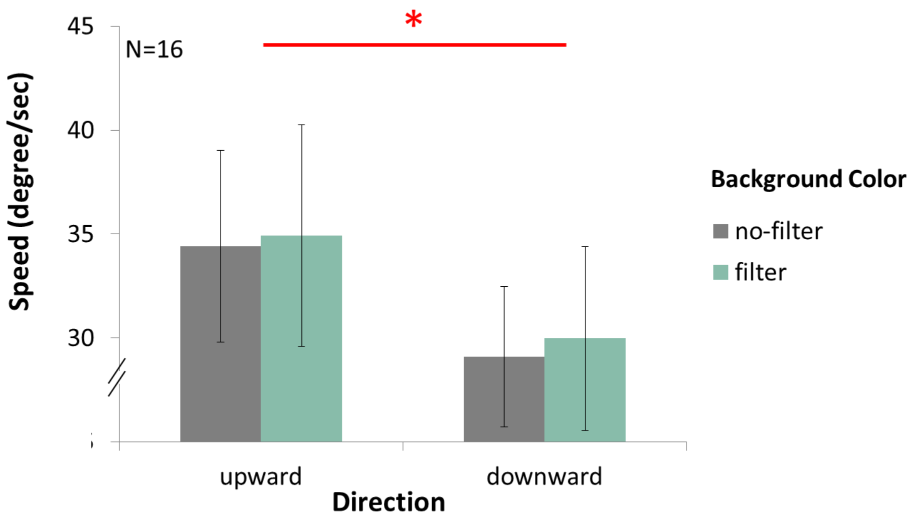

Figure 14. Results of DVA with filter. The four bars indicate the average speed (y-axis) of upward or downward motion (x-axis) in different background colors (gray for the no-filter condition, celadon for the filter condition), with standard error as error bar.

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Discussion

Again, we found better performance (higher speed sensitivity) for upward motion than downward motion, a result consistent with that obtained in Experiment 3. Nevertheless, there was no enhancing effect in the no-filter condition, showing that blue light effects on DVA in Experiment 3 and Experiment 4 were probably not due to mechanism of ipRGCs. Perhaps, it was due to S-cones, as Long and Garvey (1988) hypothesized that DVA would be enhanced under blue light in dark-adapted condition via activation of S-cones. Future studies are needed to tease this apart.

Still, there was a possibility that the ipRGCs effect could not be triggered due to the low level of stimuli intensity. Since ipRGCs respond to light wavelength peaking at 480 nm, which looks blue for human, the gray background color in this experiment contained less short-wave light than blue background in Experiment 3 and Experiment 4. Perhaps, in this present experiment, ipRGCs activation level was not high enough to enhance DVA.

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General Discussion

In this study, we found that blue light did affect dynamic vision, while having different effects on distinct types of dynamic vision. In Experiment 1, the blue light enhancement was observed on EPA, especially on y-axis pursuit, but not on KVA. In Experiment 2, we eliminated the masking effect in the KVA task used in Experiment 1, but still found better KVA performance under orange light than under blue light. To further make sure that the differences between EPA and KVA were not due to the task per se, we tested DVA, which was similar to KVA, of vertical motion in Experiment 3. The results showed that DVA could be enhanced under blue light, particularly in downward motion. As overall DVA performance in upward condition was significantly better than in downward condition, we hypothesized that upward motion task was easier than downward motion task, and that difficulty level mattered. Therefore, in Experiment 4, difficulty level was manipulated by the high and low contrast of stimuli and background color, and the results revealed that only in the hard task could DVA be enhanced, confirming our hypothesis. Last but not the least, we tested and verified whether the blue light effect on DVA was through ipRGCs activation. Hence, a blue light filter lens was equipped on a goggle to filter out half-level ipRGC activation compared to gray background color. The results indicated that DVA enhancement under blue light was not owing to different ipRGCs

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activations we tested.

The most important finding in this study was that DVA and EPA could be enhanced under blue light, and the blue light enhancement effect interacted with difficulty levels. Our findings of DVA enhancement under blue light was in agree with Long and Garvey (1988), although we had a different hypothesis for our results. The *s-cones hypothesis* of Long and Garvey was that S-cones caused stimuli on blue background color in dark-adapted condition to look more vivid than other background colors. In contrast, we started from the activation of ipRGCs with the *ipRGCs hypothesis*, which had been proven to enhance some cognitive functions and to have relations with motion perception in animal studies. However, neither *s-cones hypothesis* nor *ipRGCs hypothesis* could present strong biological evidences that what mechanisms contribute to the enhanced DVA under blue light. Future studies should modify the current paradigm to examine the neural underpinning of the enhancement for two aspects of dynamic vision (EPA and DVA) under blue light we observed here.

Apart from the blue-light enhancement effect on DVA, we further demonstrated not only the importance of how difficulty level impacted on blue light effect, but the advantage of perceiving upward motion, compared to downward motion. It is well known that when tasks are too easy, performance would reach to the maximum and never gain any benefit no matter what variables are manipulated, so-called ceiling

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effect (Salkind, 2010). DVA in upward motion (compared to downward motion, Experiment 2 and 3) and upward motion with black target numbers (compared to gray ones, Experiment 3) was so effortless for participants that they needed only minimum capacity to complete the task, resulting in no blue light enhancement effect. Future studies could systematically manipulate the difficulty level and test the transition point where blue-light starts to exert its enhancement effect.

The blue light enhancement effect on DVA was shown not caused by different activations of ipRGCs, by using blue light filter lens in Experiment 5. The next question is: what mechanism(s) contributes to our findings here? Although the *ipRGCs hypothesis* assumed that the benefit of DVA was attributed to S-cones, the low-level features in our KVA and DVA tasks were similar, with black moving numbers as targets on either blue or orange background colors. Had the enhancement been due to S-cones, it should have had the same blue light enhancement effect on both DVA and KVA. Our Experiment 1, however, showed blue light *decrement* effect on KVA instead.

Given that blue light impairs temporal and spatial resolution (Cavanagh et al., 1987), if S cones blue light stimulates are the main factor for what we observed there, it is still a puzzle why there was improvement of blue light on the DVA performance in the current study. This indicates that there might be another mechanism dedicated

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into the process of DVA under blue light. Since blue light is known to affect cognitive functions like attention and alertness, possibly there is a crucial influence from attention and alertness that affects only DVA.

Raymond et al. (1992) demonstrated a phenomenon called *attentional blink*, a temporary suppression when doing RSVP tasks with 180-450 ms intervals between two identical stimuli. In the KVA task in Experiment 1, it showed a resembling effect as RSVP task that numbers appeared and disappeared repeatedly within short intervals. Perhaps the mechanism behind attentional blink is related to the blue light effect we observed in Experiment 1. However, this masking effect was eliminated in Experiment 2, but it still showed a similar pattern, or even greater effect, that KVA was better under orange light than under blue light. The stimuli between KVA and DVA were different merely at the moving directions. Thus, maybe there were separated mechanisms of perceiving motion in depth and motion on same plane that responded distinctly under blue and orange light.

Another practical way to clarify the mechanism was through the biological evidences. MT/V5 in human brain is thought to be related to motion perception (Dubner & Zeki, 1971), and contains large amount of direction- and velocity-selective neurons (Albright, 1984). DVA is likely related to the activation of MT/V5 brain regions since it is translational motion on the same plane, especially complex motion

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like random dots (Antal et al., 2004); KVA is associated with MST areas since it had expansion properties (Tanaka & Saito, 1989). However, neurons in MT/V5 have receptive fields with center–surround antagonism, which may lead to a phenomenon called "spatial suppression", causing stimuli increasing in size becoming hard to perceive (Tadin et al., 2011). As MT signals project to MST (Maunsell & Van Essen, 1983), possibly impairing KVA, fMRI was a potential tool to look inside the head. The different brain activations between performing DVA and KVA under blue and orange light could be compared to each other to find the decisive proofs.

The correlation of KVA and EPA in Experiment 1 was only significant under blue light, but not under orange light, indicating that KVA under blue light was impaired systematically. Brindley et al. (1966) measured the critical flicker fusion threshold of blue-, green-, and red-sensitive mechanism, and signified that only blue-sensitive mechanism was impaired. In our KVA task used in Experiment 1, the target numbers appeared at the same position of the fronto-parallel planes and refreshed quickly, in need of the ability of higher temporal resolution like CFFT measured. The lower sensitivity of KVA under blue light was probably because of the impairment originated from poorer CFFT. Based on this premise, the implication of the correlation may turn out to be that one had better dynamic vision also showed better performance on EPA and less KVA impairment under blue light. Furthermore,

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KVA without masking effect in Experiment 2 had much better overall performances than in Experiment 1, which may signified that KVA in Experiment 2 was an easier task than in Experiment 1. Also, KVA in Experiment 2 had greater impairment under blue light than that in Experiment 1, indicating a similar pattern of DVA in Experiment 4 that blue-light enhancement could only be observed in hard task. Thus, we could not conclude that blue light enhance EPA and DVA but impair KVA; blue light seemed to play an important role on explicitly enhancing EPA and DVA, and implicitly decreasing the impairment of KVA.

Until recently, researches about dynamic vision were usually aimed at diseases, measurement for diagnosis, or training for athletes. Take DVA as an example, Brown et al. (1975) learned that the reduction of DVA produced by alcohol was greater than by marijuana, which was possibly a contributing factor in alcohol-related car accidents. Another example was shown by Herdman et al. (1998), who used DVA as an assessment with above 90 % accuracy to discriminate vestibular deficits from healthy participants. As for athletic training, many software programs were developed to improve the performances of dynamic vision, such as AthleVision by Hisao Ishigaki.

However, studies on dynamic vision in psychological and biological fields are severely lacking. Although dynamic vision could not be clearly separated from other

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associated abilities, it still has its own unique properties. In real life, we usually see things in 3-D space and notice more about moving things, but studies to date focus more on 2-D static vision. Dynamic vision should be paid more attention to and we urge researchers to focus on studies that help clarify the pros and cons of the different approaches and that under what conditions dynamic vision could be enhanced. Hopefully through systematic studies, researchers can develop a general way to improve dynamic vision on brain lesion patients, athletics demanding on perceiving fast-moving targets, or even video game players.

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