Shining (Blue) Light on Creative Ability

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Given the importance of creativity for both personal and societal achievements, there have been consistent efforts to stimulate creative ability. But an important environmental factor — blue (i.e., short wavelength) light — has been relatively unexplored to date. Blue light improves a number of cognitive processes (e.g., attention, working memory and sleep) known to influence our creative abilities. In this study, we investigate the effects of blue light on enhancing creativity in tasks and compare it to the effects of walking, which has been shown to stimulate creative ability. Based on data from 21 participants over 2 weeks, we found that blue light resulted in a 24.3% increase in convergent thinking ability, while walking improved divergent thinking by 18%. We discuss the implications of the findings within the context of UbiComp research. To the best of our knowledge, this is the first systematic examination of the impact of blue light on convergent and divergent thinking ability.

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INTRODUCTION

Creative ability has played a key role in societal advancement. Innovation in every aspect of life depends on creative people and processes. Creativity has been associated with workplace success [83, 77], the creation of new social institutions [54] and psychological well-being [59, 25]. Understanding how to foster creativity thus can have enormous impact on our personal well-being and the future development of society.

While the diversity and ubiquitousness of the creative process make it challenging to come up with a unanimously agreed upon definition of creativity, in recent decades, a standard definition involving originality and appropriateness has emerged [71]. Creative ideas are considered to be not only novel but also appropriate in a given context. While creativity is a complex process with many facets, it has been widely accepted that the dual processes of divergent and convergent thinking [31, 23] play a crucial role. Divergent thinking fosters variability and originality: it involves making use of available information in a novel way to produce multiple and alternative solutions. Convergent thinking, on the other hand, focuses on identifying "correct" answers in a well-defined context by using decision-making strategies and logical search. Without the evaluation process of convergent thinking, the generative process of divergent thinking would result in mere novelty or pseudo-creativity [23].

Given the wide-ranging impact of creative ability, there has been a consistent focus on enhancing it. To this end, creativity training has been shown to improve divergent thinking and problem solving across domains and applications [76]. According to Eisenberg et al. [29], depending on the requirements of a given task, external rewards combined with internal motivation can significantly improve creativity. Physical activities, including running [37, 39], dancing [38] and cycling [22], can also improve divergent thinking. Oppezzo et al. [57] found that even just walking at a normal speed improved divergent thinking performance. However, the impact of physical activities on convergent thinking is not as well-established. No significant improvement in convergent thinking was found after walking [57], and vigorous exercise was shown to have mixed effects [22].

While the creativity research community has discovered a diverse set of methods for enhancing creativity, a crucial environmental factor — the impact of blue (i.e., short wavelength) light — has been relatively unexplored. The human biological process uses light as a cue to synchronize with the external environment and is particularly sensitive to the short-wavelength spectrum [79, 17]. Blue light has been consistently shown to impact a number of cognitive processes, e.g., attention [16], information processing [51], working memory [88] and sleep [89]. Creative ability is known to depend on some of these cognitive processes as well, including attention [36], working memory [87] and sleep [15]. As such, blue light exposure could potentially impact our creative abilities. A systematic examination of the impact of blue light on divergent and convergent thinking thus might not only help us in better understanding the biological basis of the creative process but might also enable a completely new set of methodologies for stimulating creative ability.

In this paper, we report on an *in situ* examination of the effects of blue light exposure on convergent and divergent thinking. To contextualize our findings, we also compare the impact of

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blue light with walking, which has been shown to improve divergent thinking [57].

The contributions of this paper are:

- To the best of our knowledge, this is the first study that investigates the effects of short-wavelength light on creative ability. We examine and compare the impact of blue light exposure and walking on both convergent and divergent thinking. Given that mood can influence creative ability, we also investigate how these interventions might impact arousal and valence.
- Based on tests from 21 participants over 2 weeks, we find that walking improves free-flowing divergent thinking while blue light enhances convergent thinking. This is consistent with previous findings about the different neurological and attentional requirements of these two creative processes. We also find that compared to blue light exposure, walking significantly improves both self-assessed arousal and valence.
- Finally, we contextualize our findings and discuss the unique opportunities for interventions to improve creativity. The tests we used in our study operationalize creativity in a basic way without requiring domain knowledge. Creativity required in our day-to-day activities can be more complex and subtle. Our findings presented here are a first step for understanding mechanisms that might enhance creativity. However, further research is needed to investigate to what extent these interventions might stimulate creative ability in real-world situations such as what might be found in the workplace. While the UbiComp community has investigated ways to improve our physical and cognitive performance, there has been little attention given to how our creative ability can be enhanced. Compared to other methods for stimulating creative abilities, both walking and blue light exposure could be significantly easier to use and adopt. In particular, a recommender system that takes creative task requirements and individual traits into consideration to help shift between divergent and convergent thinking could have broad implications in the workplace and educational contexts.

BACKGROUND

What is creativity?

The quest to understand creativity has a long history. While ancient Greeks attributed inspiration and creation to divine intervention, by the time of Aristotle, creativity was seen as a natural and individual trait [3]. Yet the diverse and ubiquitous use of the term creativity, along with cultural differences, has made it difficult to define the concept. In fact, Prentky commented that "*what creativity is, and what it is not, hangs as the mythical albatross around the neck of scientific research on creativity*" [63]. Creativity has been explored from cognitive, personality, social, environmental and neurobiological perspectives. The diverse theoretical and methodological approaches have resulted in making creativity research domain a somewhat fragmented field.

However, despite the conceptual and empirical challenges, in recent years a standard definition of creativity has emerged. In this view, creativity is bipartite: that is, it requires both novelty and appropriateness [71]. Originality or novelty is a core component of the creative process. What is conventional or commonplace is not considered creative. But, novelty itself is not sufficient since a random process could result in something that is merely unconventional. To be creative, the final idea or product must also be effective and appropriate to the context (e.g., using an umbrella as a safe alternative to a parachute might be a novel idea, but inappropriate in a particular context). Following this standard definition from creativity researchers [71, 57], we operationalize creativity as the production of *appropriate novelty*.

Assessing creativity of an Individual

Given the different theoretical perspectives towards creativity, the methodology for assessing it also naturally varies. Hocevar et al. [42] described four major categories of creativity assessment techniques. The first category involves testing for divergent thinking ability. It involves associating ideas from different contexts that can lead to originality. The second category focuses on attitude and interest tests. This approach is based on the assumption that creative persons are more interested in pursuing tasks that are challenging in terms of creativity. The third category involves personality tests with the underlying assumption that creativity depends more on personality factors than cognitive processes. The fourth category uses biographical or life-history information to assess creative talent. Of all these tests for evaluating creativity, divergent thinking assessment has been the most widely used approach.

Divergent Thinking (DT)

Guilford [41] noted the distinction between divergent and convergent thinking in his structure of intellect model. Divergent thinking involves associating ideas from different sources and producing multiple and alternative solutions. The cognitive process behind it can lead to originality, a key component of creativity. As such, a wide range of divergent thinking tests have been developed for assessing creativity. These tests include methods such as coming up with alternate uses of common objects [40], generating titles for short stories [11], and listing repercussions of a hypothetical event [20]. It should be noted that DT tests are not synonymous with creativity but are an *estimator* of potential creative ability [70].

Despite its wide use among the research community, there has been some criticism of divergent thinking tests as a tool for assessing creativity in terms of validity and reliability [73, 78]. But, Runco et al. [70] point out that most of these issues are due to the evaluation criteria (e.g. using the number of ideas generated instead of taking appropriateness and novelty into consideration). With the use of appropriate scoring criteria, DT tests can be a reliable [84, 24] and valid [68, 72] assessment of creative potential.

While some studies have reported that divergent thinking tests do not correlate well with longitudinal achievements [93], Runco et al. [70] noted that the criteria used in those studies are often inappropriate. That is, what are considered as long-term accomplishments in those studies often depend on life opportunities and extra-cognitive factors, which might not be directly related with creative ability. Runco et al. [72] argued that creative ideation is a more appropriate metric in this case as it does not depend on extra-cognitive resources. Indeed, when creative ideation is considered as a criteria, divergent thinking tests have been shown to correlate well with long-term accomplishments [58] indicating predictive validity of these tests.

In our study, we use Guilford's alternate uses test (GAU) [40]. Following the recommendation of Runco et al. [70], instead of just counting the number of ideas generated, we take *appropriate novelty* into consideration for scoring creative ability as described in the methods section.

Convergent thinking (CT)

Convergent thinking, unlike DT, is mostly used when a correct answer exists in a well-defined context and the process involves either recalling it from memory or applying conventional and logical decision-making strategies [23]. Neuroscientific studies have established the distinction between divergent and convergent thinking processes. Based on electroencephalogram (EEG) brain activity data, divergent and convergent thinking has been associated with different alpha brain wave patterns [45, 53]. In recent years, the role of convergent thinking in creative problem solving has received more attention [23, 70]. According to Eysenck et al. [31], divergent and convergent thinking are two ends of a continuum when it comes to creative ability. The compound remote association (CRA) test is widely used for assessing the convergent thinking aspect of creative ability [57].

Stimulating Creative Ability

Given the importance of creative ability in general, there have been a number of studies that focus on encouraging its development. The approaches include using incentives [29], optimizing group processes and dynamics [19], changing organizational culture [44], training and education [76, 32], and changing work structure (e.g., alternating between challenging and mindless or "rote" work) [30].

Similar to other cognitive processes, physical activity can also influence creative ability. Gondola et al. found that running [37, 39] and aerobic dancing [38] improved creativity as measured by tests including GAU. Using GAU scores, Steinberg et al. [81] reported that exercise improved creative ability independently of mood. More recently, Colzato et al. [22], based on GAU and remote association scores, found that vigorous exercise improved divergent thinking and had mixed effects on convergent thinking. Beyond physical exercise and aerobic activities, Oppezzo et al. [57] reported that just taking a walk significantly improved divergent thinking as assessed by GAU tasks. They did not find any significant impact of walking on convergent thinking based on remote association tests.

As Scott et al. [76] noted, these attempts to stimulate creative ability mostly focus on improving divergent thinking. Given that creative ability emerges from both divergent and convergent thinking, there is an obvious need to come up with methodologies focusing on stimulating convergent thinking ability as well.

Circadian Rhythms and short-wavelength light

Our divergent and convergent thinking ability results from complicated interactions among a number of neurophysiological processes. These underlying biological processes often show diurnal patterns known as circadian rhythms (*circa*: about, *diem*: a day) with peaks and troughs following a roughly 24-hour cycle. Circadian rhythms across individuals can vary, resulting in different *chronotypes* (i.e., the proverbial "night owl" and "early bird") [66].

A number of factors modulated by circadian rhythmicity are known to impact creative ability. For example, sleep — both a modulator and reflector of our internal rhythms — can impact our creativity. Cai et al. [15] reported that the rapid eye movement (REM) sleep stage improved creative ability by priming an associative network formation. Wagner et al. [90] found that the likelihood of having creative insight more than doubled after adequate sleep. In addition, sleep loss has been shown to negatively impact cognitive performance, including creative ability [65].

Similarly, attention — a biological process that reflects circadian periodicity [86] — can impact both divergent and convergent creative ability. Based on GAU scores, some studies [52, 7] report that *defocused* attention, resulting from low cortical arousal, facilitates the creative process. In other words, when it comes to divergent thinking, variable attention can improve creative ability. On the other hand, convergent thinking requires focused attention [45]. Given the impact of biological processes like sleep and attention on creativity, it has been suggested that creativity itself would be influenced by chronotype and circadian rhythms. A recent study by Wieth et al. [91], based on insight and analytical problem solving tasks, found that time of day had effects on creative ability.

The human circadian rhythm system uses light as a cue to synchronize with the external environment and is particularly sensitive to the short-wavelength spectrum. Retinal ganglion cells with melanopsin photopigment are known to respond directly to blue light in the 460 – 480 nm wavelength range [6]. Blue light is also effective in enhancing cognitive performance, including alertness and concentration. Based on EEG data, Okamoto et al. [56] found that blue light (470nm) increases the amplitude of the P300 signal, which is associated with decision making and attentional resources. Beavan et al. [10] reported that blue light was more effective in enhancing alertness compared to caffeine. It has been reported that even short-time exposure to blue light during the afternoon improves cognitive performance in the evening [55]. A recent study from Baek et al. [5] also demonstrated that blue light helped in avoiding the post-lunch dip. Taillard et al. [82] have used short-wavelength light (468nm) as a countermeasure in cars to prevent sleep and fatigue-related accidents. Given the efficacy of blue light in enhancing cognitive performance, we are particularly motivated to compare its impact on creative ability with walking which is known to improve divergent thinking.

METHOD

In this study, we used a within-subjects design to compare the effects of walking and blue light exposure on both divergent and convergent ability. The study lasted for ten days. It consisted of two intervention phases: a walking and a blue light exposure condition. For each phase, two control days were followed by three days of each intervention as shown in Figure 1.

We recruited participants for this study through mailing lists from the research division of a large corporation. Potential participants were informed that the goal of the study was to understand aspects of circadian rhythms in order to avoid any self-selection bias related to creative ability. In total 21 people (13 males, 8 females) participated. Participants included researchers, managers, administrators, an engineer, a department director, a designer, and a consultant. Each participant was given $250 as compensation at the end of the study.

Study procedure

During the initial interview, we described the study protocol and the tests in detail to the participants. Prior to the study, we installed custom software on participants' computers for collecting creativity survey responses and sending automated notifications that reminded them to take a walk or to get blue light exposure depending on the intervention day. Participants could start the daily study session anytime between 1:30 pm to 3:30 pm. We chose this time period as we were interested in observing the effects of the interventions on the post-lunch dip, which is a known circadian phenomenon [12]. If a participant could not complete the study steps for any reason on a particular day, they were rescheduled for the next day.

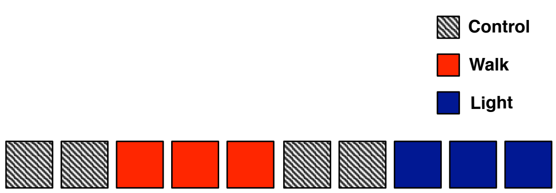

Figure 1. Schedule of the interventions across study days.

On walk days, participants took a walk outside for 20 minutes. Participants were asked to follow the intervention schedule irrespective of the weather (e.g., using an umbrella if it rained). They were also instructed to carry their phone during the walk. Using the GPS trace from the phone, we could confirm if they stayed outside for the prescribed time of 20 minutes. After returning from their walk, participants completed a short survey asking how they liked the walk using a 6-point Likert scale (0=Not At All, 5=Awesome) and if they had any social interaction during the walk.

For the blue light intervention, participants used the Philips goLITE BLU light source with a spectral wavelength range of 475 – 480nm. The light source (14.3 x 14.3 x 3.5 cm) was placed on each participant's desk ensuring that the device was within their peripheral vision. A similar light source has been used for circadian based interventions [82]. Participants were exposed to blue light for 20 minutes during the intervention phase. During this time, they were told to continue their regular activities (e.g., using the computer). To minimize any external effect, we asked the participants to not use the blue light devices any other time.

Assessing creative ability

We used Guilford's alternate use test (GAU) for assessing divergent thinking and the compound remote-association test (CRA) to assess convergent thinking. Participants conducted these surveys using our application. Such technology based tools for assessing creative ability have been validated [47, 60]. As the CRA task can interfere with immediately following GAU task performance, we always conducted the GAU task before the CRA task in our study, as recommended by Oppezzo et al. [57]. Participants were specifically instructed to not use any external help while completing these tests.

For the GAU task, the objective is to come up with alternate uses for common objects such as a brick or a button. For example, one participant generated "eyebrow brush" when asked about the alternative use of "toothbrush". We used a subset of task items from Fink et al. [35]. For each day participants received 3 different words and had 4 minutes to come up with alternate uses for the given words. As mentioned in the background section, the number of GAU responses (*ideation*) alone is not a good metric of creativity. The responses were thus analyzed in two phases following Oppezzo et al. [57]. In the first phase, a coder filtered out inappropriate answers. Appropriateness was determined based on the following criteria: the response had to be different from the given use (e.g., 'cleaning teeth' is not an appropriate alternate use for 'toothbrush'), had specific usage and had feasibility. A second coder randomly scored 10% of the responses showing good agreement (Cohen's kappa, $\kappa = 0.83$). In the second phase, we focused on novelty — the uniqueness of the response. Following the recommendation from Runco [69], we used 15% as the threshold for uniqueness. In other words, if more than three participants provide the same response, then it is not considered as novel.

We used the compound remote association (CRA) tests developed by Bowden et al. [14] for assessing convergent thinking. In this test, participants came up with a matching term that connects or combines with the given three word set. For example, given the words "cream/skate/water", the correct answer is "ice". Reaching a solution requires convergent thinking since participants need to retrieve and combine semantically distant information for connecting these three words. CRA does not require any specific domain knowledge. It has been well validated [26, 75] and widely used for assessing creative thinking [57, 48].

For each day, participants completed ten of these tasks with 30 seconds for each test[1]. We ensured that the tests were consistent across days in terms of difficulty level by taking the overall completion rate from the original study [14] into consideration. The responses from the participants were matched against the correct answers.

[1]You can find the CRA tasks used in our study at **https://github.com/saeed-abdullah/creativity-ubicomp-2016**

Mood and creativity

Mounting evidence suggests that mood and emotion affect creative ability. A number of studies have shown that positive mood can increase divergent thinking [4, 27]. But, positive mood has not been found to improve convergent thinking [92]. Negative mood and affect are also known to narrow the focus of attention [67]. More importantly, it has been reported that low dopamine levels improve convergent thinking, while divergent thinking has been associated with elevated dopamine level [18]. Indeed, Hommel et al. suggested that convergent thinking is associated with negative mood [2]. Given the relation between mood and creativity, we also collected arousal and valence (positive and negative affect) data. According to the "Circumplex Model of Affect", all affective states arise from the interaction between the independent and orthogonal neurophysiological processes of arousal and valence [62].

Participants reported valence and arousal on control days (prior to the creativity tests) and intervention days (twice each day — before and after the interventions). Based on the Circumplex model [62], the desktop application displayed a vertical axis for arousal and a horizontal axis for valence with a range of -200 (low) to $+200$ (high) values. Subjects were asked to click on the scale reflecting their feeling "right now". At the beginning of study sessions, participants also reported when they went to bed the previous night and when they woke up that morning.

RESULTS

Our dataset consists of $2,482$ GAU and $2,295$ CRA task responses. Each person provided an average of 11.28 and 10.43 GAU and CRA responses per day, respectively. On average, each participant also completed 9.57 sleep surveys, 3.0 walk experience surveys, 38.28 mood responses (arousal and valence) throughout the study. We filtered out 9 incomplete sessions which was 4.28% of the total dataset.

Divergent thinking

As mentioned before, we used appropriate novelty in GAU responses as the divergent thinking score. In our dataset, the average divergent thinking score over all participants increased during walk days (11.46 ± 0.64) while it dropped after light exposure (9.58 ± 0.73) compared to control days (9.71 ± 0.49) as shown in Figure 2.

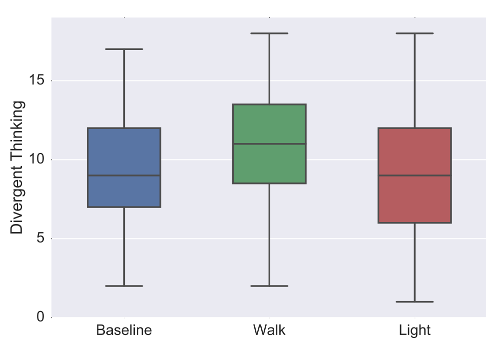

Figure 2. Averaged divergent thinking score over all participants across all days for all study conditions.

We used a linear mixed-effects model to further analyze the relationship between divergent thinking and the interventions. We used study condition as fixed effects and participants as random effects. We also considered sleep duration, gender, education level, and day of week as control variables. We found a significant effect of study condition on divergent thinking score ($F(2, 173) = 8.072, p < 0.001$). However, the control variables were not significant: sleep duration ($F(1, 173) = 0.15, p = 0.69$), gender ($F(1, 19) = 0.015, p = 0.9$), level of education ($F(2, 18) = 0.2, p = 0.81$) and day of week ($F(4, 173) = 0.351, p = 0.86$). So, in subsequent analyses, we used a simpler model, with study condition as fixed effects and participants as random effects. We fitted the model by maximizing the restricted log-likelihood using the nlme [61] package from R [64].

Model	Effects	df	F
Divergent Thinking (GAU)	Intercept	1, 178	119.6^{***}
	Study condition	2, 178	8.25^{**}
Convergent Thinking (CRA)	Intercept	1, 178	53.93^{***}
	Study condition	2, 178	4.18^{**}
Arousal	Intercept	1, 178	57.28^{***}
	Study condition	2, 178	13.86^{***}
Valence	Intercept	1, 178	49.51^{***}
	Study condition	2, 178	8.98^{***}

Table 1. ANOVA test of fixed effects for linear mixed models. *:** $p <= 0.001$**, **:** $p <= 0.01$

Model	Effects	Coefficients (SE)
Divergent Thinking (GAU)	Walking	$1.59\ (0.48)^{***}$
	Light exposure	$-0.384\ (0.5)$
Convergent Thinking (CRA)	Walking	$0.39\ (0.24)$
	Light exposure	$0.72\ (0.25)^{**}$
Arousal	Walking	$36.5\ (6.95)^{***}$
	Light exposure	$13.63\ (7.13)$
Valence	Walking	$26.13\ (6.51)^{***}$
	Light exposure	$3.19\ (6.69)$

Table 2. Coefficients and standard error of fixed effects in Table 1. For all coefficients, control day is the reference category.

Compared to control days, there was a significant increase in the divergent thinking score during walk days ($1.59 \pm 0.48, p = 0.001$) as shown in Table 2. During the days with blue light exposure, there was a non-significant decrease compared to control days ($-0.384 \pm 0.5, p = 0.44$). Visual inspection of the residual plots did not reveal any departure from the equal variance or normality assumptions. Further post-hoc analysis using Dunnett's test showed that the divergent thinking score is significantly higher during the walk days compared to control days with $p = 0.002$ and a 95% confidence level. There was no such difference between light exposure and the control days ($p = 0.66$). Moreover, effect size of the linear mixed model ($R^2 = 0.63$) indicates that it explains a good deal of variance of the GAU scores, similar to the effect size of walking on divergent thinking reported by Oppezzo and Schwartz [57].

In other words, walking outside for twenty minutes had an immediate effect in significantly improving divergent thinking. The average increase in the divergent thinking score across all participants during the walk days was around 18% compared to the control days. But, for convergent thinking, there was no such improvement.

Convergent thinking

We used correct CRA task responses as the convergent thinking score. As shown in Figure 3, average convergent thinking scores over all participants improved after light exposure (3.64 ± 0.33) compared to walk (3.34 ± 0.32) and control (2.93 ± 0.26) days.

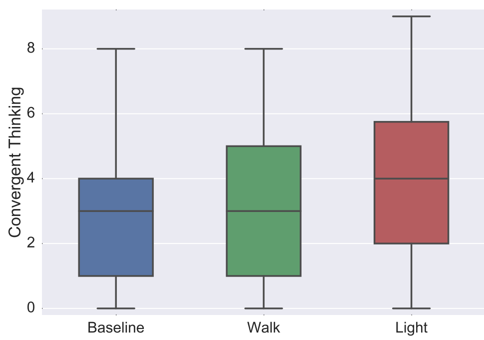

Figure 3. Averaged convergent thinking scores over all participants across all days for all study conditions.

To model the effects of study condition on convergent thinking, we used a linear mixed-effects model with correct CRA count as the dependent variable, study conditions as fixed effects and participants as random effects. We also added sleep duration, gender, level of education and day of week as control variables. We found study condition had a significant effect on the convergent thinking score ($F(2, 173) = 4.16, p = 0.01$) while control variables were not significant: sleep duration ($F(1, 173) = 0.05, p = 0.82$), gender ($F(1, 19) = 0.41, p = 0.52$), level of education (($F(2, 18) = 0.41, p = 0.67$) and day of week ($F(4, 173) = 1.13, p = 0.34$). Using a simpler model with study condition as fixed effects and participants as random effects, we found that during light exposure days, the convergent thinking score improved significantly ($0.72 \pm 0.25, p = 0.004$) as shown in Table 2. But, there was no such significant improvement during walk days ($0.39 \pm 0.24, p = 0.11$). Visual inspection of the residual plots did not reveal any departure from the equal variance or normality assumptions. Post-hoc analysis based on Dunnett's test showed that the correct CRA score improved significantly with blue light exposure compared to control days ($p = 0.009$) but not during walk days ($p = 0.2$). The effect size ($R^2 = 0.65$) of the model also indicates that it explains a fair amount of variance in CRA scores.

Thus, blue light exposure resulted in significantly improving convergent thinking ability. The average increase in the convergent thinking score during light exposure days was around 24.3% compared to control days. However, it did not have any significant impact on divergent thinking. In other words, the impacts of walking and blue light exposure are very different as measured by divergent and convergent thinking tasks.

Impact of walking and light exposure on mood

As mood and emotion might have a contrasting impact on convergent and divergent thinking, comparing the effects of interventions in this regard allows us to further validate our findings. That is, given that walking improves divergent thinking, it should result in positive mood and the effect of light exposure should be opposite resulting in either neutral or negative mood.

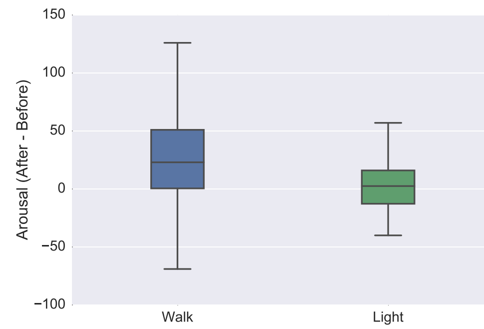

Figure 4. The difference between post- and pre-intervention arousal across walking and light exposure days. Means are averaged over all participants over all days.

As mentioned in the methodology section, participants completed arousal and valence surveys both before and after the interventions. There was no statistical difference between arousal during control days and pre-intervention arousal during the intervention days ($F(2, 178) = 1.172, p = 0.31$). The difference in post- and pre-intervention arousal averaged over all participants significantly improved after taking a walk (31.77 ± 6.63) compared to light exposure (2.12 ± 4.93) as shown in Figure 4. Using a linear mixed-effects model with study conditions as fixed effects and participants as random effects, we found that arousal was significantly higher after walking compared to control days ($36.5 \pm 6.95, p = 0.0001$) as shown in Table 2. There was no statistically significant difference between arousal after blue light exposure and control days ($13.63 \pm 7.13, p = 0.06$). Participants rated walk experience using a 6-point Likert scale (0=Not At All, 5=Awesome) and also indicated if there were any social interactions during the walk. A higher-rated walk experience resulted in an increased arousal score ($19.89 \pm 7.93, p = 0.01$). However, there was no statistically significant relationship between social interactions of the walk and change in arousal ($-12.07 \pm 13.85, p = 0.388$).

Similar to arousal, there was no significant difference between valence during control days and pre-intervention valence during the intervention days ($F(2, 178) = 0.42, p = 0.66$). The difference in pre- and post-intervention valence averaged across all participants during walk (32.90 ± 7.217) and blue light exposure (5.39 ± 6.48) days are shown in Figure 5. Using a linear mixed-effects model with study conditions as fixed effects and participants as random effects, we found that valence was significantly higher after walking compared to control days ($26.13 \pm 6.51, p = 0.001$) as shown in Table 2. There was no statistically significant difference between valence after blue light exposure and valence during

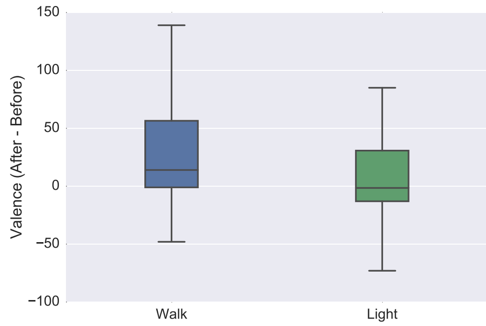

Figure 5. The difference between post- and pre-intervention valence across walking and light exposure days. Means are averaged over all participants over all days.

control days ($3.19 \pm 6.69, p = 0.63$). A better reported experience during walking resulted in higher increase in valence ($22.74 \pm 8.79, p = 0.01$). Similar to arousal, the relationship between social interactions during the walk and change in valence was not statistically significant ($p = 0.43$).

DISCUSSION

In this study, we focused on understanding and improving the dual-process of creative ability as assessed by GAU and CRA tasks. To the best of our knowledge this is the first study that investigated blue light as an intervention for stimulating divergent and convergent thinking. Using data from 21 participants spanning over two weeks, we found that blue light exposure can significantly improve convergent thinking while walking improves divergent thinking, irrespective of gender, age, level of education, day of week and sleep duration, which we controlled for. The relatively high R^2 values (R^2 = 0.63 for effect of walking on divergent thinking and R^2 = 0.65 for blue light exposure on convergent thinking) indicate that these interventions explain a fair amount of variance of the creativity test scores. We also did not find any evidence of learning effects for GAU (F(1, 6) = 5.03, p = 0.07) and CRA (F(1, 6) = 1.99, p = 0.21). In other words, practice does not improve GAU and CRA score, which is consistent with previous findings [57].

Our results build upon, and are consistent with previous findings. As mentioned in the background section, walking has been shown to improve divergent thinking [57]. A number of studies have also shown that attention can affect divergent and convergent thinking differently. Kauffman [46] suggested that *defocused* attention is a key component of novel idea generation. Examining meditation practices, Colzato et al. [21] found that divergent thinking ability decreases after focused attention based sessions compared to flexible and unrestricted attention-based sessions. The attentional cost of walking, even at a normal speed, is significantly more than sitting or standing [49]. We think that the shared cognitive resource of attention might get divided during walking and the resultant defocused attentional state would allow an increased divergent thinking ability.

Convergent thinking, on the other hand, has been associated with controlled cognition and bottom-up cognitive processes [45]. Given that blue light is known to improve vigilance and attention [89, 10], it can have more positive effects on convergent thinking than divergent thinking. A number of EEG based studies have found divergent and convergent thinking result in different types of brain activities — divergent thinking is associated with higher alpha power and more synchronization while convergent thinking results in stronger desynchronization in the alpha band [34, 45]. Blue light has been shown to result in reduced alpha activity and desynchronization [5, 33] which could potentially explain our findings about convergent thinking.

In other words, the two different aspects of creative ability — divergent and convergent thinking — involve distinctly different neurophysiological processes with contrasting attentional focus requirements [45]. While convergent thinking ability benefits from focused attention, divergent thinking requires defocused attention corresponding to a longer attentional span. As such, the intervention requirements for stimulating these two opposing cognitive processes are very different as evident from our findings. Walking in outside environments results in defocused attention, which helps to improve divergent thinking. On the other hand, blue light exposure, which is known to increase attention and focus, has an immediate positive effect on convergent thinking.

Our findings also show that blue light and walking had opposing effects on arousal and valence. As these findings reaffirm, walking and blue light exposure appear to impact our cognitive processes in different ways. The resulting impact of these interventions on mood and the subsequent improvement in the dual-process of creativity are consistent with well-established prior findings [4, 27, 2]. Walking increased positive mood and resulted in improved divergent thinking while blue light resulted in neutral and negative mood which improved convergent thinking.

While these are interesting findings with potential implications for a wide range of applications, we also note that these results are solely based on GAU and CRA tests. Given the complexity and diversity of creative processes in our everyday life, these tests understandably do not capture all possible aspects of our creative ability. As such, future studies should investigate the effects of these interventions in different contexts with concrete real-world creativity tasks.

In the following subsections, we discuss potential implications of our findings.

Implications on stimulating creative ability

Given the importance of creative ability, there has been a long line of research on stimulating creativity. These attempts include creativity training, shifting perspectives, rewards focusing on intrinsic and extrinsic motivations, and cognitive simulation. Some of these methods are well-validated in terms of their positive effects on creative ability. For example, from a meta-analysis of over 70 studies, Scott et al. [76] reported that using appropriate training methods can significantly improve ideation (number of ideas) and originality. But, they also noted that these attempts are mostly focusing on improving divergent thinking. As creative ability emerges from both divergent and convergent thinking, specific methods to improve one's convergent thinking as described here is fundamentally important.

Moreover, these suggested methods like creativity training often attempt to manipulate individuals' creative processes directly. As such, they require a conscious and persistent effort from users. As Oppezzo et al. [57] noted, easily adoptable methods like asking individuals to take a walk at their natural pace or as based on the findings from our study, simply turning on the blue lamp on their desks are more preferable and potentially more efficient. More importantly, given that the impact of blue light and walking did not depend on gender, age or level of education, these interventions can potentially be used across a wide range of people.

As dual-process theory on creativity suggests, the creative thinking process often requires shifting between analytic and associative thinking phases. It has been suggested that creative individuals can alter between these phases in response to task demands more effectively [28]. Given the interaction between divergent and convergent thinking throughout the creative process, a number of research studies have suggested focusing on enabling shifting between these different modes of thinking based on task demands for better creative output [80]. As blue light and walking have opposing effects on evaluation and ideation processes, future research should investigate how a combination of these easily adoptable interventions can potentially be used to facilitate the suggested shifting of thinking mode in order to stimulate creative ability. That is, walking could be helpful during the idea generation phase while blue light exposure can aid in the subsequent evaluation phase.

The creative process might also depend on domain and individual traits [46]. Basadur et al. [9] suggest that the process of ideation and evaluation are invoked in varying degrees depending on the domain. That is, domains with higher emphasis on problem finding will focus more on ideation while solution-implementation focused domains would invoke evaluation process more frequently. Beyond domain specific tasks, individuals can also vary in their creative process invocation. That is, some individuals are predisposed to ideation while others are more focused on evaluation. Howard-Jones et al. [43] suggested that a key barrier to creativity is the notion of this 'fixation'. Overcoming these idiosyncratic tendencies to engage in creative phases can significantly improve individual's creative ability. For example, individuals who show a disposition to engage more in convergent thinking will benefit from interventions enabling them to have more ideation (e.g., walking). Similarly, those who are more proficient in imaginative thinking might benefit from interventions shifting to convergent thinking (e.g., blue light exposure). As such, there is an opportunity for novel UbiComp systems that enable shifting between divergent and convergent thinking by taking individual traits and task demands into consideration. Such automated systems for balancing between divergent and convergent thinking processes can potentially facilitate creativity across domains, particularly in making scientific breakthroughs [74].

Implications for a dynamic light system and a smart workspace environment

The effect of light on us is diverse and complex. In particular, when it comes to our circadian systems, light is often the most important environmental factor. Light modulate our neural and physiological processes depending on the wavelength, time, duration and intensity of exposure. These non-visual effects of light include improving mood and long-term memory [85, 8].

Given the non-visual impacts of light, there have been a number of recent studies that focus on the impact of dynamic lighting systems in the workplace. Such lighting systems have been shown to improve productivity, mood, and sleep quality of office workers [85]. Varying light parameters including temperature and illuminance have also been used in educational setups. Barkmann et al. [8], based on their nine-month long study, reported that students under variable light conditions (illuminance and color temperature) performed significantly better than the control group.

Our findings here about the efficacy of light exposure in significantly improving convergent thinking further reinforces the importance of dynamic light systems that are adaptable to the varying needs of the situation and the individual. Such a dynamic system would be particularly helpful in enabling individuals to shift between phases of divergent and convergent thinking modes and optimizing the creative process as mentioned above. Beyond creativity, these systems could also be used to tune productivity and mood. A dynamic lighting system, as a result, has the potential of being indispensable in a workplace environment, in particular for the educational and scientific research domains.

It should be noted that these biological processes (e.g., mood and attention) reflect circadian rhythms. In general, a variable and adaptable lighting system could help ensure circadian stability. For example, it has been shown that circadian instability in shift-workers can be minimized by the appropriate use of light [13]. Jet lag, another form of circadian disruption, could also potentially be reduced by light exposure. Beyond that, lighting systems also have implications for mental health — blue light has been used to prevent seasonal affective disorder (SAD) [50].

While there has been an increasing focus from the UbiComp community on health and smart-home environments, systems that focus on enhancing our cognitive ability in accordance with our biological system are still lacking. We believe there is a potential opportunity for developing circadian-aware technology [1] — systems that play to our biological strengths (and weaknesses). Towards that end, a system that focuses on stimulating our creative ability by providing appropriate support, depending on the task needs along with taking individualized circadian rhythms into consideration, could help to significantly expand the current realm of ubiquitous computing.

LIMITATIONS

Our sample size was relatively small and consisted of people who were highly motivated. We can thus only generalize our results to populations with similar backgrounds. For future work, we would like to investigate the effects of these interventions in a larger and more diverse population. In particular, it will be useful to investigate the impact of blue light among college students who mostly are late chronotypes and often do not have a stable sleep routine.

GAU and CRA tests have been used extensively in the creativity research literature. However, the subtle and multi-faceted nature of the creative process means that our day-to-day creative activities can have different constraints and requirements (e.g., designing a product). In some contexts, creativity can also be part of collaborative and social processes, requiring different assessment methods than GAU and CRA tests. While this study is a first step in linking blue light, walking, and creative ability, there is much work to be done in extending these findings beyond the basic GAU and CRA tests. Future work will do well to evaluate the efficacy of these interventions in broader and more concrete contexts, particularly focusing on product, environmental, neurobiological and social perspectives.

Our interventions were also applied during a specific time of the day. Future investigation is required to assess if the impact of these interventions remains similar throughout the day. Given that walking and blue light exposures only have short-term effects, we did not balance the intervention order during the study. Nevertheless, it would be useful to confirm in future work that there are no carryover effects due to the order of intervention.

CONCLUSION

Progress and innovation in every domain depend on creativity, which results from the interaction between divergent and convergent thinking. Given the importance of creativity, a number of methods have been proposed for stimulating creative ability. However, most of these methods only focus on enhancing divergent thinking; yet convergent thinking is equally crucial for our overall creative ability. Given these motivations, we undertook the first study to investigate the impact of blue light — a key factor in circadian modulation — on our divergent and convergent thinking. We found that walking improved divergent thinking while blue light exposure increased one's convergent thinking ability. These results allowed us to generate implications and ideas for circadian-aware creativity enhancement tools. For instance, a recommender system could facilitate the shift between divergent and convergent thinking modes by taking task demands and individual traits into consideration and applying appropriate interventions in order to help improve creative ability across diverse domains, from educational to scientific research contexts. Our findings with regard to the positive effects of blue light on improving creative ability also underline the need for more dynamic and circadian-friendly lighting systems that can adapt to the varying needs of individuals in both home and workplace environments. Examples of personalized systems capable of enhancing cognitive abilities, including creativity, productivity, and alertness, as a result of taking the user's underlying biological basis into consideration, could significantly broaden the impact of ubiquitous computing.

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